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THE REAL DEFECT AND ITS NONDESTRUCTIVE CHARACTERIZATION

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ABSTRACT - Nondestructive test techniques to evaluate defect severity and component degradation are typically based on transmission of energy into the material to be inspected. The capabilities of such techniques are controlled by physical phenomena which generally don't coincide with inspection requirements. This paper reviews several recent developments (mainly in ultrasonic and eddy current testing) which highlight the state of the art.

Some recent advances to expand the range of applying nondestructive tests are represented by ultrasonic microscopy for mapping very small defects, by EMATs to measure fretting wear, and by the detection of leaking pipes and valves by acoustic emission. The process of extracting signals which can be conclusively interpreted will be the subject of case studies with combinations of ultrasonics, eddy current and radiography inspections. The use of low cost computers to map defects and to interpret signals will also be discussed. The performance of current ultrasonic inspection technology to repeatably detect and describe defects will be discussed with data from the PISC experiment and from a series of in-service inspections on nuclear components.

INTRODUCTION

Nondestructive testing can be an art, a science or a trade. This overview is intended to provide a connection between these three evolutionary phases. I shall present particular aspects of selected technologies which bear directly on practical applications by showing achievements to solve field problems. The presentation will begin with promising techniques, followed by present day solutions, and end with a discussion of the performance of the "trade".

The following topics will be covered:

(1) Ultrasonic microscopy and leak detection as new technologies,

(2) Electromagnetic ultrasonic transducers which widen the range of application of conventional ultrasonic inspection technology,

(3) Defect assessment by simultaneous application of more than one nondestructive test technique,

(4) Microprocessor controlled equipment which improves consistency of inspection and assists in interpretation, and finally,

(5) Repeatability of in-service inspections as the ultimate test of the technology.

ACOUSTIC MICROSCOPY

The technique of acoustic microscopy has been developed only very recently. This overview shall not focus on its latest advancements, rather it shall arouse awareness of the fact that a quantum jump in ultrasonics and transducer technology has occurred.

Acoustic microscopy, operating at several hundred Megahertz offers a lateral resolution roughly ten times better than conventional ultrasonics. This has been made possible by the development of crystal transducers which overcome sensitivity variations across the transducer face while retaining high efficiency. The overview of the technique given by Lemons and Quate[10] shows the image of a cancerous lymph node, at 900 MHz with a resolution well below 5 um. This technique can also be used to map defects in industrial materials; see Ref.[1], where a map of disbonded area in the seam weld of a tin can is given. L.W. Kessler[7] showed images, made at oblique angles, of defects in ceramics, and C.C. Lee[9] determined the type of defects in hybrid microelectronic components by transmission resonance spectra and differential phase measurements.

This short overview shall be sufficient to show that a new technology has come out of the acoustics laboratory, making its entrance into the materials laboratory.

LEAK DETECTION BY ACOUSTIC EMISSION

Acoustic emission has become a laboratory tool to measure the onset of cracking and crack propagation. Its use in the field is limited due to problems, one of them being the temporary nature of an acoustic burst emitted during crack growth. Another problem is the small energy released by many engineering materials when cracking. However, when the emission is generated by mass flow through an orifice, the signal is continuous and much more energetic. Investigations have centered on valve leakage monitoring and flow through cracks in pipes and vessels. W.F. Hartmann[5] has reported that the RMS signal level for steam flow through open valves can exceed the background noise by 40 to 60 dB. However, the sound level in the frequency range of several hundred kilohertz can drop by 30 dB over a distance of 2.7 m of 10 cm diameter pipe, but in the frequency range below 10 kHz it is *essentially unattenuated*.

J.A. Baron[2] found that high frequency systems are more sensitive to small valve leakage than are low frequency systems. J. Samman and G. Forest[16] reported proportionality between RMS values of the signal and the leak flow flux through artificial leaks.

Figure 1 shows two signal levels with choked flow at constant pressure (8.50 MPa) and temperature (270°C) through a fatigue crack in a pipe; from a leakage experiment at the Chalk River Nuclear Laboratories[13]. The values of the signal level exponent with flow were 0.7 and 0.8, respectively. A similar experiment under choked flow conditions (8.5 MPa and 265°C), showed a square root law. It is conceivable that the discrepancy between both experiments was caused by a change of the cross-section of the crack by crudding and oxidizing of the crack faces during the experiment.

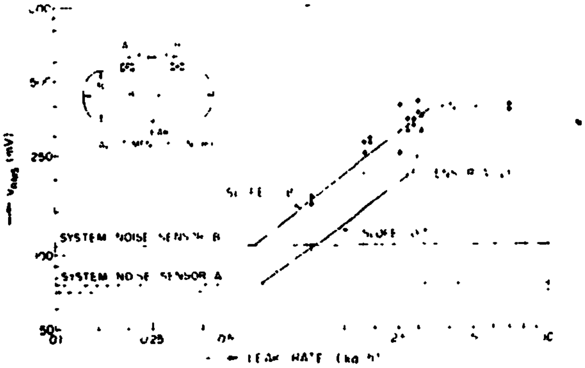

Fig. 1 Detectability of leak in the loop

When pressurized hot water flows through an orifice, it eventually flashes to steam; hence, one would expect a particularly strong signal. This is not the case, as Figure 2 shows. Under a constant pressure of 8.2 MPa, no significant change in signal level occurred between room temperature and 270°C, particularly not at 100°(13).

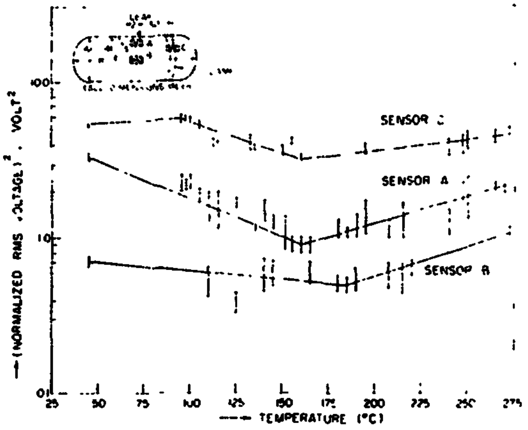

Fig. 2 Acoustic power versus temperature

To introduce leak signal detection in the field, the noise background needs to be minimized. Pattern recognition to suppress part of the noise is expected to offer an advantage.

EMATs FOR INSPECTION WITH ULTRASONIC SURFACE WAVES

I shall try to demonstrate that the accuracy of time of flight measurements on industrial components can be improved by use of surface wave EMATs.

Figure 3 shows a mock-up of piping in a generating station. Hangers to restrain the pipes had come loose and had fretted into the pipe. Since the radiation fields were very high no human could come near to do a visual inspection. Instead, remote tooling consisting of two "robots" was built to operator inspection and repair equipment. The figure shows a self aligning ultrasonic tool which was placed over the hanger.

Two 5 MHz, 1/4 in. probes were used to measure the time of flight of

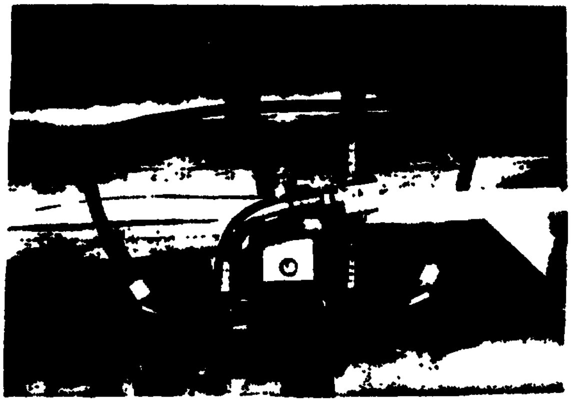

Fig. 3 Piezoelectric surface wave transducers over hanger on SS304 pipe

Rayleigh waves. They were angled about three degrees above the Rayleigh wave angle for better suppression of bulk waves. The transmitted surface wave would follow the contour of the fretting groove, taking a longer travel time with greater depth of wear. Figure 4 shows the calibration on stainless steel pipe with three different

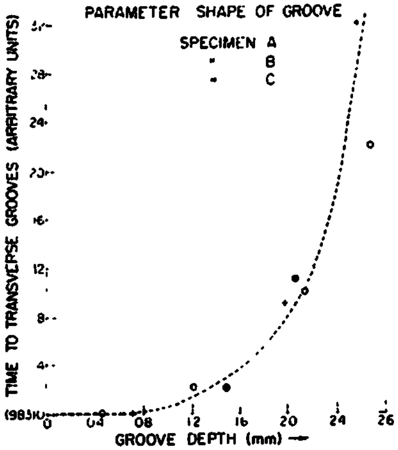

Fig. 4 Time delay versus depth of wear with piezoelectric probes on SS pipes

cross sections of the groove. The scatter was about 0.2 mm for groove depths greater than 1 mm. A successful inspection was performed at the power station. The same technique was then evaluated to inspect carbon steel feeder pipes. On these, surface roughness by mill scale ranged up to 0.1 mm RMS.

Individual high spots were considerably larger, causing time delay variations which corresponded up to ± 2 mm depth of wear(12).

The uncertainty of the travel time caused by the variation of couplant thickness was unacceptable. This variation would not be present with EMAT's, since an electromagnetic field instead of an ultrasonic wavetrain would cross the gap between probe and pipe. A research program into EMATs was then conducted by V.M. Ristic at the University of Toronto(6).

A uniform EMAT operating at 4 MHz gave the following results; see Figure 5. On a variety of groove dimensions, the scatter was about 0.25 mm, except for two samples. One sample had a polished surface whose surface wave velocity (v=2848 m/s) was low compared with the rough samples (v=3172 m/s). In another sample, a bulk wave interfered with the Rayleigh wave. The bulk wave was generated in a corner of the groove. Transit time was indeed independent of lift-off; see Figure 6. It is concluded that the accuracy of depth of wear prediction for rough pipes, from EMAT testing, were close to that measured with piezoelectric probes on the smooth stainless steel pipe and that it was far better than that with piezoelectric probes on the rough pipes.

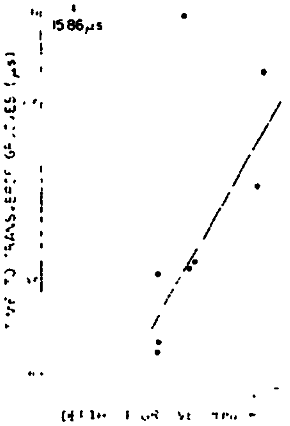

Fig. 5 Time of flight versus depth of wear with Rayleigh wave EMATs on as received carbon steel pipes

COMPLEMENTARY INSPECTIONS

The use of more than one inspection method on a particular component is often considered a luxury. However, in some cases, complementary methods are very worthwhile; this should be demonstrated by an example.

When it is difficult enough to get

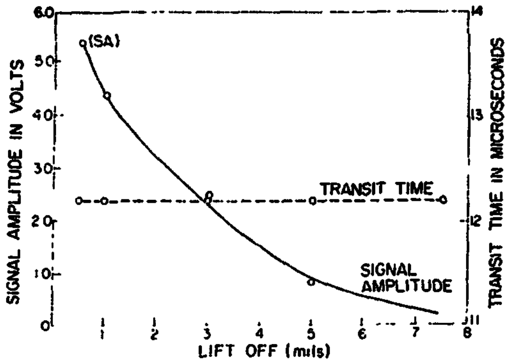

Fig. 6 Amplitude and transit-time dependence on "lift-off" on sample No. 4 with surface waves EMATs

to know the peculiarities of one test method, it is even more difficult to compare and select several test methods. There is little literature on this subject. From the innumerous possible combinations, priority should be given to those which yield relatively accurate information on desired defect characteristics by the most contrasting physical effects underlying the test. There is, for example, not much to be gained when eddy current and potential drop, or dye penetrant and magnetic particle inspections are employed complementary to one another. Not that it may not narrow down a prediction, but both techniques suffer similar restrictions and may both give the same wrong answer.

The use of both ultrasonics and eddy current to interpret surface and near surface indications on pressure tubes used in CANDU reactors is becoming common practice. The following conclusions have been drawn from such practice:

(1) The complementary nature of both methods allows easy distinction between tool steel intrusions and inclusions.

(2) For defects nearly normal to the surface, ultrasonics was more sensitive, but for strongly inclined defects, eddy current yielded better detectability.

(3) Defect depth prediction by eddy current is usually more accurate.

(4) Ultrasonics can explain eddy current indications due to localized resistivity changes which can be confused with lap type defects.

MICROPROCESSOR ASSISTED INSPECTION AND DATA HANDLING

The cost for programmed control of inspection set-up and data handling has come down so much that "intelligent" systems, not just "switchboxes", are becoming affordable. Large systems for automatic inspection do not fall into this category of equipment because they remain specialized, expensive and are usually not portable. Three categories of new equipment will be discussed.

Robots

The purpose of robots is to ensure repeatability of inspection set-up. Once an inspector has made a decision on the numerical value of a variable like probe frequency, he can store the decision in a memory. Future inspections can call up a block of decisions to repeat the inspection ad nauseam. Robots may also have rudimentary data processing capability.

Three robot inspection system shall be discussed. One system is the Eddiscan Eddy Current Instrument. It is a field instrument for detection of cracks in fastener holes. The operator uses a keyboard for data input and the system responds with a display indicating depth and position of the crack.

The Nortec 25 eddy current instrument is intended for a more general use. It also has keyboard input and display output. It can store up to 16 blocks of inspection variables.

The KB6000 ultrasonic instrument is a laboratory instrument, where input is either via pushbuttons and switches or from an external controller.

The Interpreter

Such a system processes data to reach a conclusion. This is usually not under the control of the person who developed the algorithm.

Inspection data can be incredibly complex, as seen in maps of ultrasonic echoes in stainless steel or of eddy current signals where signatures of lift-off, defect, tube support and tube conditions may superimpose. However, relatively simple algorithms can, at times, be successful. Most of the common pattern recognition techniques are not suitable for field inspection instruments; they are too slow, or the memory size exceeds practical limits.

J.L. Rose[15] has described a system to discriminate between ultrasonic signatures from weld cracks, roots and porosity. Evaluated features were rise time and secondary echoes. Pattern recognition of acoustic emission signals has been the subject of research for several years; main aim was to extract signals originating from loose parts and cracks from background noise in operating nuclear pressure vessels.

The Number Cruncher

Its "NDT intelligence" lies in between the two systems described above. The SUTARS system gathers amplitude, time delay, probe position and probe orientation from a manual ultrasonic inspection and records the data temporarily on cassette for off-line processing. Output are maps of flaw location within the geometry of the component and tables. It can also record a defect signature. The P-scan system takes amplitude, time delay and probe position data from an automatic scan to produce similar maps and tables, also still off-line.

Once a map has been obtained, one can process the data to further accentuate image details. Edge enhancement of radiographs has led to a considerable increase of image quality. Non-linear signal processing of ultrasonic signatures can improve the dynamic resolution of imaging systems[8]. Colouring the image enhances details and eases severity classification. Grey scale imaging assists the operator when interpreting an image. Figure 7 shows flaw locations drawn into the nominal and actual contours of a pipe weld[11]. Flaw severity is quite different in these pictures. Unfortunately, it is generally too time consuming to measure the weld contour prior to inspection. Imaging of both flaw and weld geometry quickly shows the location of the flaw relative to the weld contour.

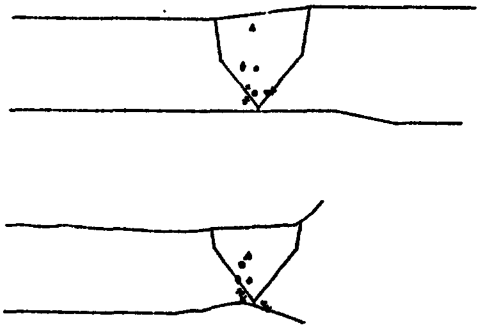

Fig. 7 Location of indications in the nominal (top) and actual (bottom) weld contour

REPEATABILITY OF ULTRASONIC IN-SERVICE INSPECTIONS

One of the main purposes of in-service inspections is to provide information for the failure prediction during continued service of not only the component inspected but also of components which operate under similar conditions and have similar quality. Its intent is to extrapolate into the future and across components. The added request for high repeatability coincides with additional problems like constraints of access and inspection time, inadequacy of documentation and component fabrication for application of advanced inspection technology, and restricted operator movements due to protective clothing. Below, the performance of in-service inspections shall be compared with published data of inspections carried out under the less demanding conditions in a laboratory or a shop.

Laboratory Experiments

A number of investigations into the performance and repeatability of ultrasonic inspections on real or idealized components have been performed. Some laboratory investigations into specific problems showed a poor performance with ultrasonics. Particularly thorough research has been done in three areas of conventional echo amplitude testing:

(1) amplitude versus defect size; (2) amplitude versus defect orientation, and (3) amplitude versus crack tightness.

The first problem led rather quickly to the judicious use of defect size/beam ratios, like in the application of the DGS diagram or the mapping of flaws with high resolution beams.

The influence of defect orientation on signal amplitude still is not realized everywhere nor in all weld inspection codes. It is simply mandatory that the beam stands normal, or at least very close to normal, on the defect surface.

The transparency of cracks is another severe problem. Fatigue cracks can be completely transparent to ultrasound, and there presently appears no better way to overcome this problem than by subjecting the volume under test to tensile stress during inspection.

The statistical variability of echo amplitude has been studied extensively. There is reasonable agreement between three sets of data. Silk[17] presented a total standard deviation $\sigma=\pm6.7$ dB; Forli[4] reported $\sigma=\pm6.0$ dB and Becker[3], estimated $\sigma=\pm6.1$ dB. If one assumes proportionality between echo amplitude and defect size, then, for two out of three predictions, the actual defect depth will be within about one half and two times the predicted defect size.

The percentage error of a depth estimate of small defects is about equal to the error for fatigue failure cycles estimates.

A number of round robin tests is currently being undertaken worldwide to more closely assess inspection performance on reactor components. The first large scale test, named PISC 1, is complete[14]. Using the echo amplitude method in accordance with ASME Section XI, it was found that vertical artificial defects had to be 60 mm deep, or about one fifth of the wall thickness, to be reliably detected. At the acceptance limit of 10 mm crack depth, detection probability was only 10 per cent. A cluster of small defects which was unacceptable when proximity rules were applied, was not reliably detected regardless of its envelope size. More comments on the results of round robin tests are contained in[18].

In-Service Inspection

Defects reported in an in-service inspection are generally acceptable, but large enough to be reportable. The information from the PISC 1 round robin test indicates that acceptable defects are not reliably detectable even under laboratory conditions. They are even more difficult to describe. Their true characteristics are unknown because they are not generally destructively examined. In the following, in-service inspection experience on regularly inspected heavy components is discussed. The inspections were generally performed in accordance with the ASME Pressure Vessel Code, Section V.

Missed Indications

All indications were not detected during each inspection. However, the number of missed indications decreased with time. Where the pre-service inspection missed 16 out of a total of 68 reported indications and the first in-service inspection missed 13, their number decreased to 8 in the following two in-service inspections. It appears that experience and development of technology with time did more to improve detection probability than in-service constraints tended to worsen it. It was also found that from 330 reported indications, 51% of the indications were confirmed in the preceding or the following inspection[12].

Echo Amplitude

A comparison[12] between 166 amplitude reportings yielded a standard deviation of $\sigma \pm 4.24$ dB. This measured standard deviation is smaller than Silk's estimate attributed to defect property variation ($\sigma = \pm 6.1$ dB), but is larger than couplant and operator variation ($\sigma = \pm 2.8$ dB)[17].

Length of Indication

A sample of 37 indications showed that reported indication lengths either varied by less than 10 mm, or that they varied by up to 100 mm; probes of 12.5 mm diameter and 25.4 mm diameter were used. The variation of 10 mm maximum was probably caused by the differences of lateral resolution of the probes. The large variation were probably related to the application of proximity rules. It should be noted that the lateral beam dimension is not checked during probe calibration following ASME Section V procedures.

Depth Dimension of Indications by Probe Movement

The sample size of seven indications is very small for statistical evaluation. Five indications remained unchanged. One indication "grew" but there is evidence of a proximity problem. One more indication "grew" from 3 to 6 mm, i.e., it remained within the beam size. Because of the low resolution of the beams used, indications were out of the range where defect mapping can be properly applied.

Predicted Type of Defects

In the evaluated sample, lack of fusion, slag, and crack indications were named. Some indications were inspected up to four times. For such indications, the first reported inspection was compared with the fourth and the second inspection was compared with the third to lessen the influence of a trend on the operator's opinion. Figure 8 shows the occurrence of combination reported. For example, a total of 47 predictions of "lack of fusion" was confirmed 18 times, it was called "slag" 12 times and was also called a "crack" once. If one tries to separate consistent defect type descriptions from inconsistent ones by the repetition of

	LoF	S	C	LoF+S	LoF+C	S+C	LoF+S+C	TOTAL
LoF	18	12	1	14	0	2	0	47
S		16	0	4	2	3	1	26
C			2	0	0	0	2	4
LoF+S				12	3	1	1	17
LoF+C					0	1	0	1
S+C						6	0	6
LoF+S+C							4	4

Fig. 8 Occurrence of reported combinations of defect types
LoF = lack of fusion,
S = slag, C = crack

the type in whatever combination, for example LoF alone, LoF+S, LoF+C, LoF+S+C, one finds that lack of fusion was consistently reported 32 times and inconsistently reported 15 times, slag was consistent 24 times and inconsistently reported twice and cracks were 4 times consistent and never inconsistent. The repeatability of a predicted type with itself is read from the diagonal and normalized by the total. It is best, namely 16 times out of 26 (62%) for slag for the single defects. Overall, the prediction of a type of defect appears not consistent enough to include defect type into severity criteria as in radiography.

It was also found[12] that 73% of 338 predictions were called fabrication defects, another 21% were named fabrication defects associated with cracking, and 6% were characterized as geometry, surface effects and parent metal defects. No mention was made of any service-induced defect.

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