Notes on the Industrial Technologies for Crack Detection and Condition Monitoring.

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1. Introduction.

Structures that are subject to cyclic stresses in normal service may develop cracks and these cracks will inevitably grow and potentially lead to in-service failure.

The reasons for cracks to develop in the first place are many and varied. Components that are working at high cyclic stress levels will simply suffer from cyclic fatigue and fail. In many cases this process is aided by discontinuities at welds or inclusions in the metal (gas or impurities). Rubbing of surfaces will produce stress-corrosion effects and the presence of corrosive agents (water, oxygen, chemicals, etc) can greatly hasten the process.

For simplicity we will refer to these generically as 'fatigue failures'.

The structures of almost any form of mobile equipment will be highly stressed and vulnerable to fatigue failure as described above. This will include aircraft, mining plant, vehicles of all sorts, cranes and the like. In some circumstances fixed structures will also be subject to fatigue failure. Examples would be offshore platforms (wind and wave action), pressure plant (pressure changes), rotating plant (such as ball mills and kilns), etc.

Manufacturers of all plant potentially subject to failure are very aware of such matters. At the design level they carefully estimate the in-service loads and develop computational finite-element models to determine the locations of high stress. They will then endeavour by careful design to minimise the risk of failure. Materials and scale-models may also be tested to destruction to gain a better understanding of the behaviour of materials and correlation with the computational work.

Owners of the assets so produced will be required to conduct periodic in-service inspections of critical components and, in some cases, replacement of certain parts are the predicted safe cycle life has been reached. This is particularly intensive in the aviation business where the safety issues are paramount. Such inspections are often driven by regulatory authorities that require reports of routine inspections to be filed. At the industrial level regulations for equipment such as pressure vessels have recently been relaxed to allow for owners to conduct their own inspections.

The need to regularly inspect highly stressed plant for fatigue failures has spawned a branch of technology generally known as Non-Destructive Testing or simply NDT. The descriptor 'non-destructive' is to set it apart from the destructive materials testing that is carried out in materials laboratories. It also implies an ability to comprehensively report on condition without damaging the structural components.

We will now consider the technology as it exists and how it typically operates in industry.

2. Non-Destructive Testing Methods.

The following is a brief description of the five common NDT methods used in industry. Research effort is being applied all the time to come up with more effective ways of achieving reliable and cost-effective inspections and there are a number of special-purpose methods in use that we will not consider here. The Comparative Vacuum Monitoring CVM) technology developed by SMS is another step along that path but, as we shall see, it makes a significantly different contribution to almost all the existing technologies.

2.1 Radiography (RT).

This is very analogous to the medical X-ray technology that we are all familiar with. A beam of radiation is released from a source point and transmitted through the object being inspected. An X-ray sensitive film on the other side records a single-plane image representing the varying densities of absorption of the radiation.

Common applications are these:

- Pipeline weld quality inspections.
- Castings.
- Checking inaccessible components (eg, aircraft wing spar).
- Conveyor belt internal condition.

The advantages of the system are that it can produce a permanent record of the inspection for future reference if required. It can be reasonably automated and has some real-time capabilities.

Disadvantages are that there are safety issues, the equipment is cumbersome, it requires at least two operators, a flim processing facility is usually required before results can be seen, and it is not good at defining the presence or dimensions of small cracks.

2.2 Ultrasonics (UT).

High frequency sound waves (typically around 1 MHz) have the ability to transmit through solids and liquids and the associated technologies are known as ‘ultrasonics’. A very useful feature is that any discontinuity or change of density produces a reflection and this can be turned into an ‘image’ by measuring the time between transmission of an ultrasonic pulse and the various return signals received. The equipment measures the time delays in nanoseconds!

The method is analogous to the ‘echo-sounder’ used on boats to display reflections from anything in the water (fish) and the bottom.

The UT method is very commonly used for precise crack detection in relatively small items. Note that it cannot be used to detect cracks on the surface – a minimum depth of around 3 mm is required to get within the ‘focal length’ of the sensor.

Transmission losses typically limit its use to a transmission path of around 300 mm. Most portable equipment displays an image from which the operator is able to determine a finding. Some newer equipment is able to digitise the image for computer analysis.

A significant disadvantage is that there is quite a degree of operator skill required and consequently the industry requires formal qualifications for UT operators. There are also some limitations in its ability to detect certain kinds of cracks but a good operator will be able to indicate the requirement for other techniques to be used.

A variation on the UT method is the use of the technology to measure wall thickness of tanks, pipes and the like. This is a very simple adaption of the technique and requires very little operator skill.

2.3 Liquid Penetrant (PT).

This method is also known as Dye Penetrant or Dye Check and is widely used to find cracks in the surface of machines or structures. The idea is simple. A coloured dye, specially formulated for the purpose, is applied to the cleaned surface of the object being tested. some time is allowed to pass for the dye to penetrate and then the surface is carefully wiped clean. A ‘developer’ in the form of fine chalk powder or similar is sprayed on and the dye will soak into the powder and produce a visible line indicating where the crack is. Another variation is to use a dye that is visible under UV light and inspect the surface with a UV lamp.

This is an old technology but it still works well. It obviously can only detect surface cracks and cannot work under paint. It is readily understood and the method can be easily learned. There is no permanent record unless a photograph is taken.

On the other hand the information it produces tells nothing about what is happening below the surface and it also doesn’t easily detect wide cracks where the capillary action is lost. It has limited resolution for very fine cracks also because ultimately it is a visible process.

2.4 Magnetic Particle Inspection (MPI).

This method is similar in application to the Dye Penetrant method but gives better results and is the most widely used in industry. A powerful magnetic field is applied to the object being inspected followed by the application of a magnetic ink or powder (typically iron filings suspended in kerosene). If there is a crack or discontinuity on or near the surface, the iron filings gather along that line.

Again, the technique is simple although there is more technique required than for Dye Penetrant. The surface must be cleaned thoroughly before the test – including paint – and the method can only work on magnetic materials! Like Dye Penetrant, there is no record unless a picture is taken.

2.5 Eddy Current Testing (ECT).

This method uses the principle of induction. By generating a high frequency current in a coil and holding that coil close to the surface of a metallic object, so-called ‘eddy-currents’ are generated in the surface of the object. The inductive effect of these eddy-currents can be measured as modulations of the current in the coil and produce useful information.

The simplest application of the idea is the paint-thickness probe. Here a small probe with a coil fitted in the end is held on the surface of the paint. Eddy currents generated in the metal underneath can be calibrated to show how thick the paint is with very high accuracy.

The widest NDT application is for crack detection on sheet metal materials. Therefore it is readily adapted to the aircraft industry to identify cracks around rivet holes and the like. It is generally used over small areas rather than for large-scale testing. A high degree of operator skill is required and therefore results can only be confidently received from a very experienced operator.

2.6 Summary.

Most of the common NDT techniques as described above have these features in common.

a) They are invasive. Few of the techniques can be used on operating machinery and in many cases the machinery or structures require some degree of disassembly. An exception would be thickness measurement where much of that proceeds in normal service of tanks and pipelines.
b) They are 'one-off' inspections. None of the techniques offer 'real-time' monitoring or any means of trending or recording crack initiation or propagation.
c) Most techniques require some operator skill and a level of interpretation of results.
d) Equipment must be accessible for operators to conduct the tests.

Most other NDT methods are variations on the methods detailed above and offer the same limitations.

3. Laboratory Testing and Associated Technologies.

Most laboratory testing involves testing to destruction and therefore not in the same field as NDT. However, the CVM Method has obvious applications for destructive testing and we need to consider these methods here. We will also look at related technologies that are relevant to the application of the CVM Method.

3.1 Laboratory Fatigue Testing.

Laboratory testing can range from something as small as a piece of metal being cycled to the point of fatigue to a complete structure, such as an aircraft, being stressed. In all cases the engineers running the tests want to know precisely when a crack develops and at what rate it propagates.

Unfortunately none of the NDT methods described above can provide that information. So in an effort to get some sort of real-time response they have employed other techniques which we will briefly describe as follows.

3.1.1 Strain Gauges.

Strain gauges are generally made from a highly resistive material etched to produce a gauge pattern and mounted onto a thin insulated base which, in turn, is glued to the material being tested. The locations and orientation for strain gauges would be carefully selected to ensure that they were very close to expected fatigue zones and yield maximum sensitivity.

As a cyclic test proceeds the strain gauges would display in real-time the strain at the point of attachment and that information, by itself would be a useful correlation to the FE model. However, if the material in the zone started to yield the strain gauge would show a DC offset proportional to the yield and give indication that a crack might be developing. Note that the strain gauge would not indicate a crack – just the possibility of a crack.

At that point it would be necessary to stop the test and bring in the conventional NDT inspection methods to examine the surface for cracks. Sometimes that might mean a complete removal of all the strain gauges making it necessary to re-install everything. The result can be a huge waste of time and considerable costs to reinstate the monitoring systems.

3.1.2 Foil/Wire Gauges.

The idea with this method is simply to place the gauge where a crack is expected and have it fail with the crack and open a monitoring circuit. The gauges are not unlike strain gauges but much longer to cover a reasonable sensing area. The conductor is relatively brittle so that it fails with minimum elongation.

The problem with this method is that the location of the failure is not always predictable and so the gauges may well not be in the right place. Some reports have said that cracks passed right under wire gauges without them breaking. If the foil should detach from the surface it will indicate that it intact and therefore create a false result.

3.1.3 Potential Difference Method.

This method is generally applicable only to test samples in testing machines. One end of the test sample is electrically isolated from the jaws of the machine. A sensitive resistance meter is connected to each end of the test piece and the resistance measured in real-time by passing a current through the specimen. A small change in resistance would indicate a reduction of area and hence the assumed propagation of a crack.

Some test laboratories have found this method very useful. Note, however, that it cannot be easily used for large scale testing as there is no ability to insulate sections for testing.

3.1.4 Visual Inspection.

Some test machines are equipped with magnifying inspection lenses focussed on the surface of the test piece. The test is periodically stopped and visual examination made. If necessary visual examinations might be supplemented by conventional NDT techniques such as dye penetrant.

3.1.4 Summary.

The methods described above are an attempt at reaching the ‘holy grail’ of fatigue testing – a reliable real-time monitoring system that provides indication of crack initiation and propagation without test interruption. Unfortunately, for the most part, they fall well short of the desired performance standards.

3.2 Condition Monitoring Methods.

Related to the methods described above is another field of specialisation called ‘condition monitoring’. Condition Monitoring is primarily used as a maintenance planning technique applied to rotating machinery and process vessels, but the same ideas can be applied to other forms of plant.

The main technologies used for condition monitoring are briefly described as follows.

3.2.1 Vibration Analysis.

Accelerometers are used to measure vibration on a machine or structure. This data can be measured periodically or continuously and the results analysed for changes. The assumption is that a change in vibration represents a change in condition and analysis of the data can then indicate what is going wrong.

3.2.2 Thermography.

The use of thermal imaging cameras to scan electrical and mechanical components is now very common in industry. Its earliest applications were in medical scanning to identify 'hot spots' that might indicate disease of some sort.

Primarily this is a periodic technique applied at intervals which may be as long as six months. It is rapidly catching up to vibration analysis as the most widely used CM technique.

3.2.3 Oil Analysis.

Another well established CM method is oil analysis. The condition assessment of lubricating or hydraulic oils and the analysis of wear particles is an extremely effective method for condition monitoring of engines, gearboxes, hydraulic systems and the like.

3.2.4 Process Parameters.

It can be argued that many process parameters such as pressure, temperature, flow, electrical current (motors) and the like are useful for condition monitoring. That is certainly true but the term condition monitoring has generally been applied to non-routine periodic inspection technologies that require specialist operation or interpretation.

3.2.5 Summary.

Condition Monitoring is very widely practiced as a means of risk minimisation when applied to the maintenance of capital assets – and it is very effective. The techniques listed above are at the core of virtually all condition monitoring programmes.

In industry, Condition Monitoring often works alongside periodic NDT inspection programmes to provide a comprehensive maintenance strategy to reduce lost production time.

Condition Monitoring works best with continuous processes (where loss of production is critical) or in high risk plant (nuclear, petrochemical, etc) where hazard reduction is vital.

4. A Comparative Appraisal of the CVM Method.

The CVM Method has been in functional service for some five years and has been shown to be able to detect the initiation of cracks as small as 250 microns in length. We will assume for these notes therefore that the validity of the method is not in question. We will refer only to its application in comparison to the methods described above.

The obvious comparisons are these.

4.1 Real-Time.

The CVM method provides real-time data while a device is under test (short-term) or in service (long-term). This is a radically different capability from any other technology and is the primary feature of the method. The digital data acquisition system developed by SMS is able to sample at up to 10Hz from one SIM or approx. 0.5 Hz from sixteen SIMs simultaneously.

4.2 Multiple Locations.

The CVM Method allows up to 16 SIMs and potentially around 100 locations to be monitored in real-time by one data acquisition system. This again is completely unique and comparable only to an array of strain gauges in operation.

4.3 Lightweight and Unobtrusive.

The CVM sensors weigh only grams and can be installed in inaccessible areas where other crack-detection methods just could not function. The siting of sensors is limited by the potential for them to be physically, chemically or environmentally damaged but in most structural situations this requires only appropriate care in installation and protection.

4.4 No Hazard.

The CVM Method presents a totally passive operating environment for the sensor and its connecting tubing. There is no power, no heat source and no energy present. This makes the method extremely attractive for hazardous environments such as oil and gas and chemicals.

4.5 Continuous or Intermittent.

The sensor pads, when installed, should maintain their integrity for years if they are not damaged. According to the need, data can be captured periodically (say weekly or monthly) or continuously. Thus the CVM can be applied to provide condition monitoring of structures either periodically or continuously. Good quality condition monitoring requires good data capture repeatability. The CVM method has excellent repeatability because the sensor is permanently applied to the measurement site.

4.6 Initiation and Propagation.

The CVM method has the capability to detect the initiation of a crack when it is less than 1 mm in length. The basic sensor can then trend the development of the crack qualitatively as the flow increases with more galleries being breached. More sophisticated versions of the CVM method can quantitatively trend the crack propagation by direct measurement using an indexing system. This enables a test to proceed to a pre-determined point and then shut-down – all automatically. No other such capability exists outside the CVM Method.

4.7 Simplicity.

The CVM method is simple and inherently reliable. It is generally easy and quick to install and test procedures can be applied to verify the integrity of the sensor at commencement and in-service. No special training or certification systems are expected to be needed to regulate the use of the CVM method as it gains application acceptance.

4.8 Flexibility.

The standard sensor for use with the CVM method is a polymer pad into which galleries are cast. However, a sensor can be formed by numerous possible methods including incorporating the sensor within the body of a structure and SMS have demonstrated the veracity of this technique for application to lap joints on aircraft fuselages. This again is a completely unique feature of the method.

5. Market Applications.

The Comparative Vacuum Monitoring Method developed by Structural Monitoring Systems Limited in Perth, Western Australia, has been shown to offer many unique and valuable features to the crack-detection industry worldwide.

5.1 Replace Conventional NDT?

The new CVM Method will not be seen as a replacement for conventional NDT because it is of a different kind. Conventional NDT has developed from the need to do periodic inspections on machinery and structures and to thereby certify the integrity of these devices. The physical act of visual inspection in many of those situations is rated as highly as the application of the technology. This has been evidenced to-date by the almost total lack of interest from the NDT industry in the method.

However, it will potentially be seen as a method that can extend the possibilities for crack monitoring in many situations currently impractical for conventional NDT. This will take time for the industry to grasp but it will surely come.

5.2 Fatigue Testing Applications.

The CVM Method is already being seen by the fatigue-testing industry as something entirely new and valuable. The CVM Method offers for the first time an ability to set up a test and allow the results to be managed electronically with a high degree of confidence.

Consequently the aviation industry and all its associated service providers represents the primary source of interest in the product to-date. In this application the CVM Method is effectively replacing the conventional NDT methods or the other methods developed to provide some sort of real-time reporting. It is likely however, that in the short term conventional NDT methods will be used to validate the findings of the CVM Method after failures have been detected.

Parallel to the aviation industry are a number of other industries where extensive structural testing is conducted. This might include military vehicles, commercial vehicles, all forms of mobile mining and exploration plant, lifting machinery and the like. For these industries the primary issues may be functional reliability rather than the safety issues that drive the aviation industry. However, they will almost certainly be interested to evaluate the CVM Method and potentially to apply it.

5.3 Other Applications.

The product that has been currently developed by SMS is designed to meet the needs of the industries as described above. However, the application of the CVM idea has potentially numerous applications across industry and in due course many of these applications will be researched and developed.

6. Summary.

These notes have endeavoured to identify where the CVM Method fits into the established crack detection technologies and applications.

It has been shown that, for the most part, the CVM Method is unique and will open up possibilities for real-time monitoring of crack initiation and propagation that has just not been possible with existing technologies. It does not present a threat to suppliers or users of established technologies.

Until a range of standard sensor types has been developed and widely used there will need to be a reasonably high level of application engineering applied to customers needs. This will be particularly so for condition monitoring applications rather than for laboratory testing. Consequently there will potentially be a cost-premium for the application of CVM initially until in-house skills in the application of the technology are developed.

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