Evaluation of A Novel NDE Technique for Surface Monitoring using Laboratory Fatigue Specimens

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Abstract: This paper summarises an evaluation of some novel NDE techniques, which may allow the detection of numerous small cracks (less than 1 mm surface length) over a large area. The effectiveness of three novel NDE approaches was evaluated on a large polished specimens representing part of a bulkhead. The main NDE techniques used were 1) Holographic laser interferometry, 2) Comparative Vacuum Monitor ("CVM"—a vacuum-based system), and 3) Laser ultrasonics. Conventional NDE techniques were also used for comparative purposes.

The laser ultrasonic technique did not work well, as it required very highly polished surface conditions for successful crack detection. The CVM and laser interferometry both worked well, but the laser interferometry technique requires complex data collection and interpretation. Data collection with the CVM, which uses leaks between alternating capillaries of slight vacuum and atmospheric pressure to detect cracks, is much simpler, although it required calibration to relate pressure leakage to the size and number of cracks. The capillary system can be left on a component and can simply be connected to the interrogation equipment to perform the inspect ion. Sensitivity of the CVM is controlled by the wall thickness between capillaries.

When surface treatments such as peening are employed to extend service fatigue life, crack detection becomes extremely difficult, a situation exacerbated by the fact that peening may introduce many small surface discontinuities. As such, the investigation was expanded to include using the CVM on peened surfaces. The system demonstrated its ability to detect changes in crack configuration as cracks developed; thus, the CVM shows promise for crack detection on degraded surfaces.

INTRODUCTION

High-performance high-strength aircraft components such as wing carry-through frames are currently designed to extract the maximum performance from the materials used. The high level of stressing and limited fracture toughness lead to:

(i) more rapid fatigue crack growth, and
(ii) a reduced critical crack length for fracture.

In practice, this results in the possibility of failure from very small cracks. At the same time, the efficiency of the design methods used for these components results in highly *uniform* stressing, with the result that a large number of fatigue cracks will develop at approximately the same rate, leading to the phenomenon of multi-site cracking. These circumstances can place extreme demands upon the use of Non-Destructive Evaluation (NDE) methods for finding and characterising defects; in many components, NDE cannot reliably detect cracks at a sufficiently early stage. When life-extending surface treatments such as glass bead peening are also employed to extend service life, degrading the performance of NDE methods, it becomes almost impossible to detect the small crack arrays which ultimately may be life-limiting.

Ideally, an NDE technique for small cracks would offer the potential for component monitoring (i.e. the ability to continuously record any indication, or to be interrogated

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intermittently as to progress of the indication) as well as being used for one-off inspections.

Three criteria were established and a number of NDE techniques were compared on their potential to meet these criteria;

(i) could detect multi-site cracking (<1mm),
(ii) would work on peened surfaces, and
(iii) if possible left in-situ.

The last specification was given lower weighting due to its difficulty in implementing on fleet aircraft. The results are summarised in Table 1.

Table 1: Evaluation of potential NDE techniques.

NDE Technique	Multi-site cracking (40%)	Work on peened surfaces (40%)	In-situ capability. (20%)
Standard Eddy Current	Yes – slow	Sometimes	No
Standard Ultrasonics	Yes - slow	No	No
Dye Penetrant	Yes	Sometimes	No
Laser Ultrasonics	Yes	No	No
Comparative Vacuum Monitoring	Yes	Yes	Yes
Holography Laser Interferometry	Yes	Yes	No

Based on this table a research program was established looking at laser ultrasonics, CVM and laser holography. Where possible the results from these three techniques were compared with conventional NDE techniques.. The research program was broken down into two parts: an assessment of each technique with relation to multi-site cracking and an assessment in relation to detection of cracks in peened surfaces. Some recent work has looked at the effectiveness of in-situ NDI techniques under high strains.

EXPERIMENTAL TECHNIQUE

Two types of specimens were tested. The first, for detecting multi-site cracking, was a thick dogbone specimen (360mm x 140mm x 30mm) with a 150mm radius on the specimen face. The surface was polished using 1000# paper to provide a surface roughness between 2-10μm. The second type of thin dogbone specimen was 360mm x 30mm x 6.5mm but was peened according to McDonnell Douglas Aerospace[2] specification PS14023 [1]. This involved peening all surfaces with glass beads to 8 Almen, providing a surface roughness between 30-60μm. The larger specimen was used for the unpeened trial because such a specimen always displays multi-site cracking; the thinner specimens usually failed from a single corner crack, but were suitable for the peening trial.

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[2] McDonald Douglas Aerospace is now Boeing St Louis.

The specimens were loaded with a standard fighter aircraft loading sequence derived from wing root bending moments on the F/A-18 aircraft. The sequence comprises some 22000 turning points and a peak stress of 396MPa. One sequence is referred to as 1 program [2]. Some recent work has involved comparing performance of the CVMS with that of crack gauges on double side-edged notched 4340 steel specimens subjected to high strains to simulate F-111 cold proof loading. The radius of the notch was 15mm, and the specimens, 4mm thick, 75mm wide and 260mm long.

NDE TECHNIQUES

Comparative Vacuum Monitor System

The CVM System was invented as a means of detecting and monitoring cracking in-situ [3]. This variant of the system is based on applying a self-adhesive pad (called a sensor), one side of which contains a series of capillaries alternating between atmospheric pressure and a slight vacuum, Figure 1. A crack is detected when it grows sufficiently to allow air to leak from an atmospheric capillary to a vacuum capillary, leading to a change registered on the pressure differential gauge, which monitors any background (steady-state) leakage. This gauge can be set to trigger an alarm at a certain change in pressure or can be continuously monitored and recorded. Continual improvements were made to the CVM during the test program, until the final version was completed before the peened specimen was tested.

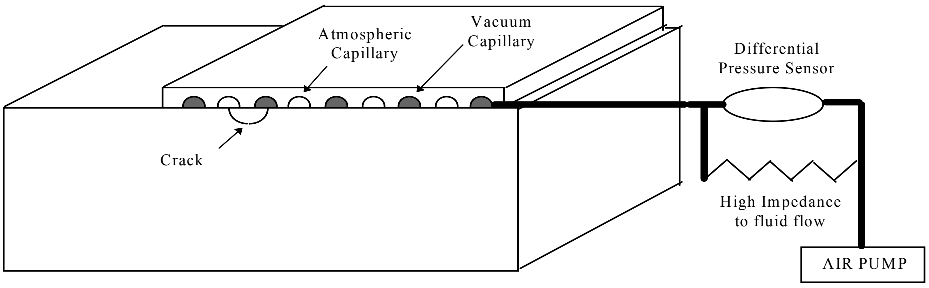

Figure 1: A schematic of the CVM system applied to a cracked specimen.

The sensitivity of crack detection is effectively determined by the capillary wall thickness. A wall thickness of 1mm would clearly allow only cracks longer than 1mm to be detected. With this in mind the CVM sensor finally adopted for these trials had a wall thickness of 250μm. Subsequent trials on real structure had a wall thickness closer to 100μm.

Once detected, the crack can be precisely located by pinching off the capillaries one at a time, until there is a response from the gauge (ie. it returns to the original zero setting), indicating that the crack is beneath this particular capillary.

Laser Ultrasonics

The laser ultrasonics NDE was performed by Ship Structures and Materials Division (SSMD) in their experimental rig [4]. Lasers can be used to generate ultrasonic signals in place of piezoelectric transducers, thus allowing rapid non-contact scanning of large areas. Laser ultrasonics is at present primarily a laboratory tool, although it is being developed worldwide with a view to application to aircraft.

The laser ultrasonic measurements were performed using laser generation and piezoelectric detection with both generation and detection occurring on the curved surface. Transmission and reflection laser ultrasonic measurements were made at a wide range of generator and detector locations but always with wave propagation parallel to X direction ie. perpendicular to the crack direction.

Holography Laser Interferometry
The portable HLI testing system was supplied and initially set-up by Bob Clark from the University of NSW, Australian Defence Force Academy (ADFA) [5]. The completion of the testing was performed by the authors. The ADFA set-up is technically holographic interferometry of which there are three main types. In this case the most common type was used, termed double exposure holographic interferometry; the interference is between two optical fields stored on the same plate, each optical field having been recorded at separate times, with the object in slightly different states (ie. different stress state) [6-8]. The authors made a number of changes from the initial set-up due to equipment failure, and attempts to improve image contrast and the number of interference fringes. The holographic set-up [7] is shown in Figure 2.

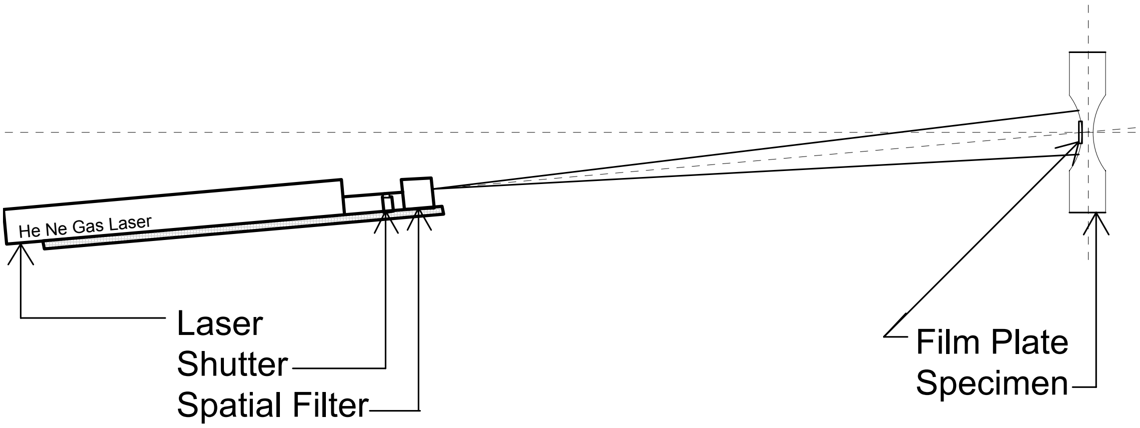

Figure 2: Schematic of portable laser holographic system. Note thatthe whole process is done in a dark room, so that ambient light will not affect the holographic film.

Two guides were placed on the specimen to locate the holographic plates, just off the surface. The holographic plates had to be mounted and removed in darkness, so a light proof skirt was placed around the test rig with a tube leading to the laser, Figure 4. The interference hologram detects any surface displacement differences; therefore for each plate an image is captured at a high and low load to provide the interference fringes. After some initial trials it was decided to coat the surface with a white lacquer (ARDROX 8901W White Background Lacquer). This provided enhanced contrast and reduced the focused reflection from the specimen surface [7]. Due to the testing environment and the time constraints at AED all the options for creating holographic interferograms were not explored. The system used made it very difficult to determine the correct plate exposure, except by trial and error [9].

RESULTS OF TRIAL ON MULTI-SITE CRACKING

The large specimen was tested in a computercontrolled 1MN test machine cycling at 3 Hz. After every spectrum block the test was stopped and the specimen was loaded to 50% of peak load. A holographic laser interferometry (HLI) image was taken and the CVM system checked to see if any cracks had been located. The front of specimen was monitored with the CVM system and the rear with the HLI system, alhough at the end of the test an HLI image was taken of both sides.

Figure 1: Large specimen set-up with laser holography on rear-face (left) and CVM system sensor (right) on front face. The reason for the shroud is to reduce external light when holographic plates are being exposed.

The laser ultrasonics reported possible cracking after 14 programs, although as the testing continued these were shown to be surface anomalies, not cracks.. The CVMS system indicated its first crack after 25 programs and the HLI after 26 programs. With the addition of one block the CVMS had indicated three cracks and the HLI two cracks. After 29 blocks both techniques were indicating multiple cracks, testing was stopped and conventional NDE used. Fluorescent dye penetrant inspection under load confirmed the presence of all the cracks suggested by the CVMS and HLI. Both eddy current and conventional ultrasonic inspections could confirm only the presence of the largest cracks. A microscopic investigation of the specimen surface revealed multiple cracks at the locations determined by the CVMS and HLI ranging in size from 100μm to 2mm, Fig.3 and 4.

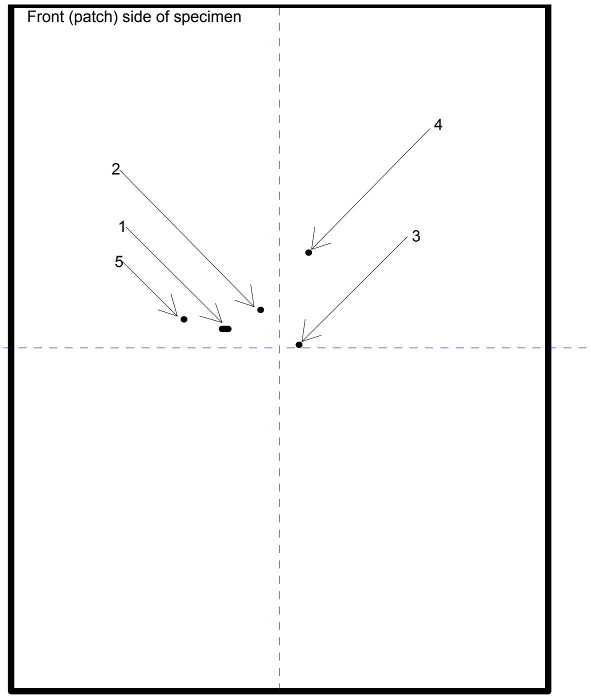

Figure 3: Cracks located by CVM system on front face of specimen.

Optical measurements of the front face cracks indicated the following surface lengths: Crack 1 - approx 2.2mm, Crack 2 - approx 1.0mm, Crack 3 - approx 1.1mm, Crack 4 - approx 300µm and Crack 5 - approx 400µm.

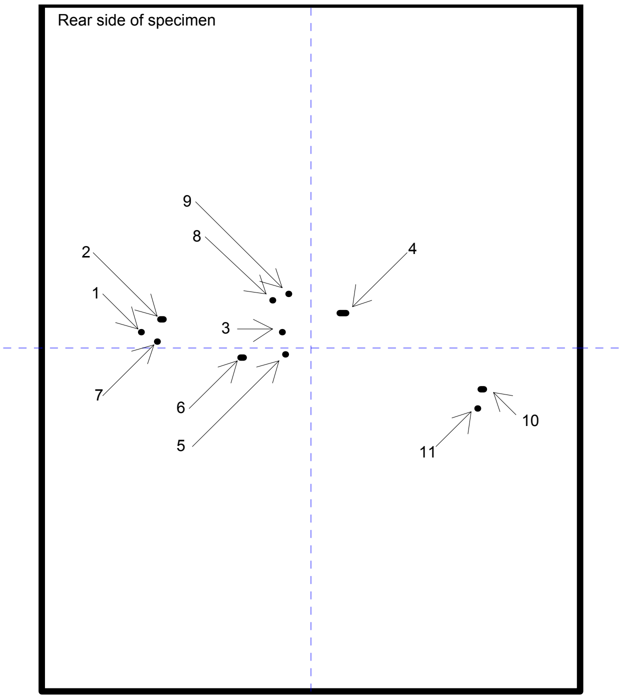

Figure 4: Cracks located by laser holography on rear-side of specimen

Optical measurements of the rear face cracks indicated the following surface lengths: Crack 1 - approx 400µm, Crack 2 - approx 1.2mm, Crack 3 - approx 300µm, Crack 4 - approx 2.3mm, Crack 5 - approx 350µm, Crack 6 - approx 1.1mm, Crack 7 - approx

400μm, Crack 8 - approx 300μm, Crack 9 - approx 300μm, Crack 10 - approx 1.1mm and Crack 11 - approx 400μm.

The difficulty with HLI is interpretation of the holograms, an example of which is shown in Figure 5. It is worth noting that while Fig. 5 is a 2D picture, the holograms are in fact 3D images of the surface. This is not visible in the printed images. ADFA is developing an automated computer imaging system to assist the operator in extracting the correct information

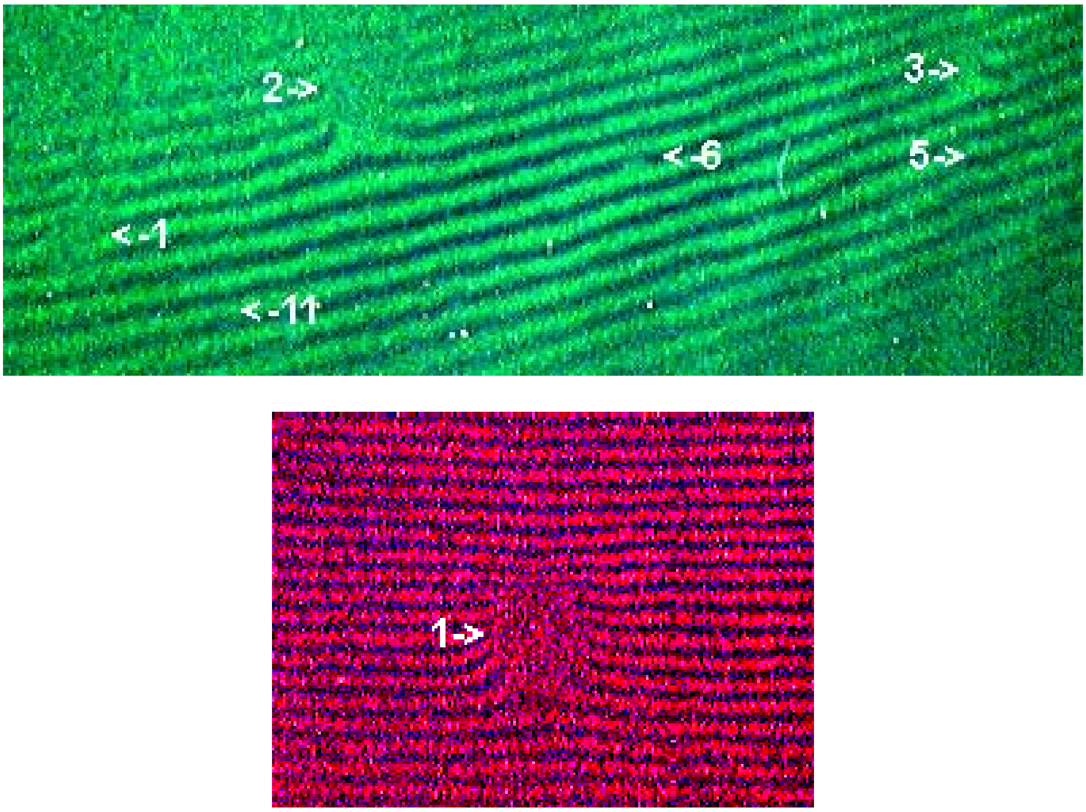

Figure 5: Typical laser holograms (interferograms) showing the presence of cracks as distortions in the curves. The top figure is for the back face of the specimen and the lower figure is for the major crack detected under the CVM sensor.

It was also very difficult from the way each technique was set-up to determine the size of each crack. The CVM system was just one patch covering the complete area, so while capillaries could be pinched to determine the location of cracks and give a comparative crack size it was not possible to give a real crack size. The differential pressure sensor picked up the change for the whole patch, which could be caused by one big crack or a number of little cracks. However, this could be overcome with smarter patch design. It is difficult to measure real crack size with HLI due to the reason explained earlier, although again a relative size comparison is possible between the cracks on the face. More research would be needed to develop a capability to determine the true crack size.

Despite their problems both the CVMS and the HLI were able to detect multi-site cracking. The laser ultrasonics had problems relating to the surface finish of the specimen and the radius of curvature, and was not able to detect any of the cracks. Of the two systems, the CVMS was the simplest to use and interrupt. Due to the problems with laser ultrasonics the system was not used for any further testing, although research is still being conducted into its effectiveness.

RESULTS ON PEENED SURFACES

Detecting cracks on peened surfaces has always been a problem due to the increased surface roughness from the peening process. It was surmised that an NDI technique that was comparative (ie. could “zero out” surface roughness) would be the best approach. With conventional NDI techniques (eddy current and ultrasonics) use on a peened surface can lead to a two-fold increase in the minimal reliably detectable crack size. Based on AMRL’s earlier experience with the CVM system and laser holography, both appeared to have the potential to find cracks with minimal reduction in sensitivity.

A small test program was conducted [10,11] to determine if CVM and HLI could be used to detect cracks on peened surfaces.. An additional complication was the fact that this specimen type generally fails from a corner crack, so the NDI methods had to be applicable to these corner regions. Figure 6 shows the CVM as set-up on the specimen and the capillaries in the patch after the specimen was broken. The capillary wall thickness is 250µm. Due to a limited number of specimens the HLI was used post CVM detection to determine whether it could also be used to detect cracks on peened surfaces.

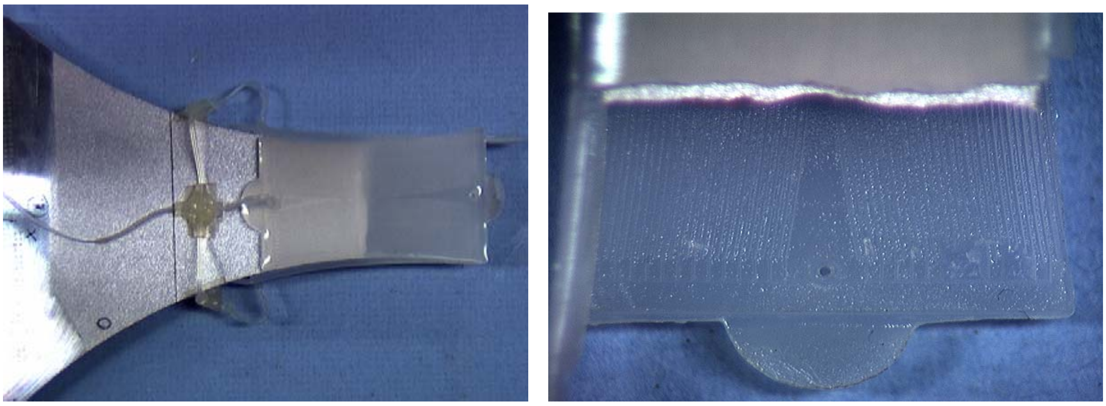

Figure 6: Picture of CVM system on a peened specimen surface. The capillary wall thickness is 250µm.

The first specimen was used to generate a CVM output vs. crack depth curve. The specimen failed from a corner crack at the identified location, and the progress of the crack throughout the test was determined by quantitative fractography. Figure 7 shows the CVM response with number of programs, as well as the crack growth behaviour. Figure 7 suggests strongly that the CVM is responding in a fairly sensitive manner to crack growth, once the initial atmosphere/vacuum connection has been made.

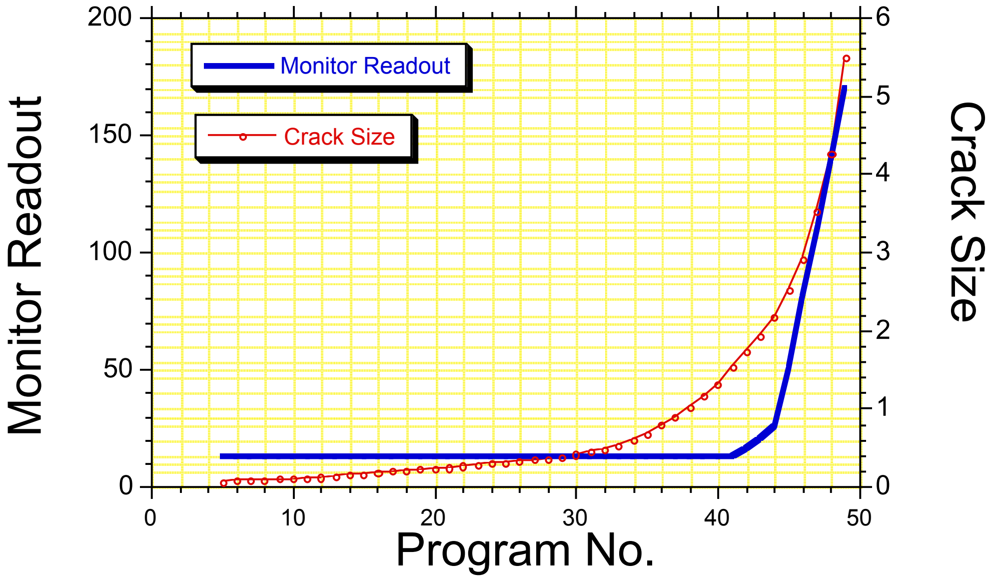

Figure 7: Plot of CVM system output (mB) versus crack depth(mm) per spectrum program number

The second peened specimen was used to confirm that the CVM was responding to crack growth, as opposed to spurious effects; the CVM alarm was set to a trigger level consistent with a crack of approximately 500µm in surface length (based on earlier observations). Once the alarm sounded, the crack was located and eddy current and ultrasonic inspections performed. The specimen was broken open to reveal the size of the crack, Figure 8. The crack surface lengths measured were 720µm on one face, and 780µm on the other. Neither of the traditional NDI techniques located a crack, although based on experience with cracking in peened surface this is not surprising. .

Figure 8: The crack size detected by the CVM system (720µm by 780µm).

These results demonstrated that the performance of the CVM system in detecting cracking was not significantly degraded by the presence of a peened surface. The HLI also detected the cracks found by the CVM, although as stated earlier, interpretation of the holograms was extremely difficult.

RESULTS FROM HIGH STRAIN TESTING

Some more recent work as part of the RAAF F-111 Sole Operator Program [12], using the CVM system on High Strength Steel (4340) specimens has also shown the effectiveness of this technique as a laboratory system. The objective was to determine whether either system could be left in place, in a very difficult access area, for the term of the fatigue test – 15months and still provide real time results. The difficulty with this is that the component used can, in some critical locations, experience ±20 000με. In this case the CVMS was compared with standard crack propagation gauges (CPG)[3] to determine which would be better suited to a full scale wing fatigue test.

Figure 9: Comparative Vacuum Monitor System 2000 used for the high strain trials. The picture shows the larger field unit and the smaller laboratory unit.

The CVM system zero condition (under a range of loads from 0%-70% peak load) was very stable at around 5-10mV (0.3-0.5mB). The trigger level was set at 40mV (2mB). The CPG varied from 35mV at 0% peak load to 40mV at 70% peak load. The trigger level was set at 130mV. Each technique was providing real-time monitoring of the specimen. Once cracking was detected the gauge or sensor was removed and a magnetic rubber inspection (MRI) was performed to confirm the size and location of the cracks. It should be highlighted that the MRI was conducted with zero load on the specimen (simulate wing test conditions), not the more favourable pre-loaded condition.

Five 4340 double side-edged notched specimens were tested, three with the CVMS and two with crack gauges. The results are shown in Table 2.

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[3] Crack Propagation Gauges (CPG) – Micro-measurements type TK-09-CPB02-005/CP

Table 2:

Specimen	CVMS-1	CVMS-2	CVMS-3	CPG-1	CPG-2
CA Loading, R=0.1	85kN then 112.4kN	112.8kN	112.5kN	112.2kN	112.4kN
Detected Crack Length	330μm (0.013")	330μm (0.013")	No detected crack	N/A	N/A
Cycles at Detection	1,881,000 then 58,000	547,000	98,000#	CPG failed after 4000 cycles	CPG failed after 4000 cycles
Additional cycles to failure	20,898	14,595	13,960		

Test stopped after 98,000 cycles, CVMS removed and area inspected with MRI – note the MRI could not confirm the presence of a crack.

There are a number of interesting points from Table 2. First, the CPG could not withstand the high strains and tended to fail, through a number of problems mainly associated with the bonding process. . In the two cases where CVMS detected cracks (CVMS-1 & CVMS-2) the cracks were approximately 330μm in length (ie. slightly above the wall thickness of 250μm) In the last CVMS-3 the CVM system detected a crack after 98000 cycles. The CVM sensor was removed at this time and a magnetic rubber inspection performed – which found no crack. However based on the short time to failure after the MRI, a crack must have been present at the time and missed by the MRI.
In summary the CVM system proved to be very reliable even at high strains. While more testing is needed, the CVM system has the potential to be a very effective real-time non-destructive inspection technique for regions in which access is difficult.

DISCUSSION

This paper summarises research conducted over a number of years looking initially for a NDI technique which;

1. Could detect wide area multi-site cracking,
2. Would work on peened surfaces.

later expanded to include;

1. Real time data acquisition,
2. Long term stability.

Of the variety of NDI systems examined in the laboratory only the CVM system met all these requirements. The CVM has proven to be a reliable and accurate laboratory technique for the detection of cracks. Nevertheless, care still needs to be taken in bonding the sensor to the specimen, to ensure good adhesion, and with specifying the capillary wall thickness (which controls the size of crack detected). If the capillary wall is too thin (100μm), it tends to deflect and pull away from the surface with the cycling loading of the specimen providing false indications.

The CVM system is being assessed on a number of structural component fatigue tests being conducted at DSTO. While the CVM system has been an excellent laboratory technique, substantial durability testing is needed before it can be used as a long-term real time technique on fleet aircraft.. A program of durability testing is due to commence soon. This includes durability testing on three RAAF P3 Orion aircraft, using four different locations, and environmental testing at DSTO. Another consideration for aircraft maintainers is performance over a painted surface; the specimens reported in this paper involved non-painted surfaces.

CONCLUSION

1. The CVM system is capable of sensitive and reliable crack detection in laboratory fatigue testing. The system is contained and easy to operate, and can be manufactured to a range of configurations and sizes to cover large areas.

2. Care must be taken in specifying the capillary wall thickness (which controls minimum crack detection size).

3. Care must also be taken to ensure the sensor is well adhered to the surface. .

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