POD ASSESSMENT USING REAL AIRCRAFT ENGINE COMPONENTS

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INTRODUCTION

The economic drive towards using military aircraft beyond their initial design life has created a great interest in damage-tolerance (DT) based maintenance philosophy. The DT approach relies on routine nondestructive inspections (NDI) and requires the NDI performance to be quantified in terms of probability of detection (POD). From the POD-flaw size relationship, the detection limit of inspection techniques, in terms of flaw size, is established and then used to calculate safe inspection interval [1].

For POD measurement, a large number of flaws are inspected by the same NDI techniques that are used during maintenance. Inspection results are then verified and the detection rate is determined as a function of flaw size. Since POD at a given flaw size is the mean value of a finite number of flaws of that size, a confidence level (usually 95% lower confidence) is assigned to the mean POD. The flaw size detectable at 90% POD with 95% confidence is defined as the detection limit of the inspection technique and is used as the initial flaw to calculate the number of cycles it would take for the flaw to grow to the dysfunction size. The safe inspection interval is taken to be half of the calculated number of cycles.

The most common approach for POD measurement is to make specimens representing the actual part and introduce artificial flaws such as EDM notches or fatigue cracks to simulate service-induced cracks. This approach is used by the USAF and described in the AGARD LS-190 report [2]. Although this approach is practical, in many situations it is not economical or possible to simulate the exact component or flaw geometry. Another approach uses the actual field inspection data and the crack growth curves to obtain POD [3]. After a crack is detected in a part, the associated crack growth curve is used to estimate crack sizes missed in previous inspections. If sufficient number of detected and missed cracks exists, then the data can be evaluated statistically to obtain POD. This approach is economical and provides representative

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POD. However, it requires accurate and consistent data collection and recording over a long period of time in order to obtain sufficient data. Alternatively, one can use actual parts that are known to contain flaws and perform NDI demonstration using the same field inspections. This approach is both representative and practical, however, flawed parts are not often available. The latter approach was employed in the present study.

In this paper, experimental procedures and results of POD measurements on service-expired components from a military aircraft engine are described. The service-induced low cycle fatigue cracks present in the components are compared with artificial cracks in terms of physical characteristics and NDI response. The effect of crack location and shape on POD is also discussed.

POD EXPERIMENTS

Component

Ten service-expired 7th stage compressor disks from the J85-CAN40 engine (Figure 1) were used for POD measurements. These parts had remained in service beyond their designed safe-life-limit due to logistic problems with part replacement and as a result, low cycle fatigue cracks, originating from the bolt holes, were present. The cracks were not visible to the naked eye and therefore the parts were ideal for such assessment. The disks are fabricated from precipitation hardened martensitic stainless steel (AM355). The thickness of the disks in the bolt hole region was 1.8 mm (0.07") and the bolt hole diameter was 4.6 mm (0.18"). Each disk had 40 bolt holes and therefore there were 400 inspection sites which were adequate for POD development.

Inspection Procedures

Liquid penetrant inspection (LPI) and manual eddy current inspection (ECI) are currently used by the industry to detect bolt hole cracks in aircraft engine parts. These techniques were assessed along with a number of other NDI methods including magnetic particle inspection

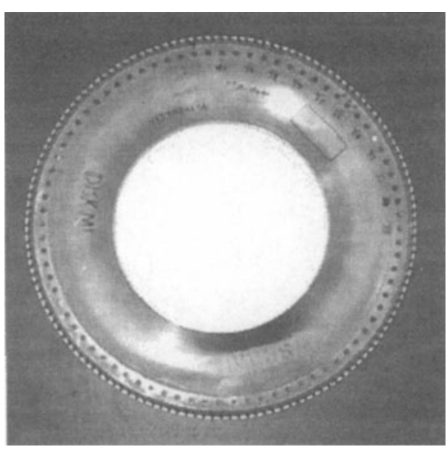

Figure 1. A seventh stage compressor disk from the J85-CAN40 engine.

(MPI), ultrasonic method and a new optical technique (Edge of Light, EOL) which is developed at NRC. Details of inspection procedures are provided in [4].Two automated eddy current systems were also evaluated; one was an experimental system developed for IAR by Tektrend International and the other one was a commercial system manufactured by Scientific Instruments Inc.

Verification Tests

After completion of all NDI, the existence of cracks was verified by pry opening of every bolt hole and examination of fracture surfaces under an optical or a scanning electron microscope [4]. Under the microscope, the service-induced LCF cracks were easily distinguishable from the rupture failure due to their smooth and oxidized surfaces, and the maximum crack length was measured. The specimens that did not reveal a crack on the fracture surfaces were further examined on the bolt hole surface to make sure that a crack was not missed during the pry opening operation. If a crack was found, its surface length was measured.

Calibration Specimens

Forty test specimens were prepared from actual compressor disks by removing material from between the holes. Half of the specimens were used for the creation of fatigue cracks in the laboratory. In these nearly rectangular specimens a 2.8mm hole was drilled and a 1.4mm EDM notch was cut in the hole. These specimens were then loaded under cyclic tension-tension loading conditions. For cyclic loads of 67-670kg (150-1500lbs), applied at 10 Hz, crack initiation occurred at about 5000 cycles and grow at about 0.1mm per 1000 cycles. Cracks from 0.2mm to 2mm, as measured using optical microscopy, were grown in the specimens. Almost all cracks grown using this approach were through-cracks that appeared close to rectangular in shape. After loading was completed, the EDM notch and the 2.8mm hole were drilled out to a 4.6mm hole diameter that is the same size as the actual bolt holes. In addition, whole compressor disks were also used to fabricate inspection test sites by drilling new holes, 4.6 mm in diameter, between existing holes in four disks, providing 160 virgin sites. EDM notches of various sizes (0.2 to 2mm long) were placed in 15 of these holes. EDM notches were also rectangular in shape and had a width of 0.17 mm open on both surfaces.

Statistical Analysis

Based on the destructive verification tests, the number and percentage of cracks detected (hit), missed or incorrectly identified (false calls) were found for each procedure. For POD analysis, values of 1 and 0 were given to "hit" and "miss", respectively. For "hit/miss" type data generated on the basis of one inspection per crack, either the log-normal or the log-logistic distributions can be used [2]. A comparison of POD curves using these two distributions was made [5] and the log-normal function was selected for determining POD and confidence limits. The mathematical functions underlying this distribution are described in the literature [e.g. 2,5-7]. The functional forms of both the log-logistic and the log-normal distributions include location and scale parameters which must be estimated using a parameter estimation procedure. The Range Interval Method (RIM) and the Maximum Likelihood Estimators (MLE) have been suggested [2]. RIM has been shown [5] to be highly dependent on the interval size and the approximation for intervals with POD of 0 or 1. In contrast, the MLE method does not require any information other than the actual data. Therefore, the MLE method was used in all cases.

RESULTS AND DISCUSSION

Bolt Hole Cracks

Examples of different crack types seen in the compressor discs are provided in Figure 2. Most holes had a single radial crack, either open to both top and bottom surfaces (through-cracks) or only to one surface (corner-cracks) or neither surfaces (middle- or internal-cracks). Most cracks were small corner cracks that eventually grow to larger through-cracks. There were also a few middle-cracks; many of these initiated at what appeared to be voids or inclusions in the material. The crack faces were smoother than the ruptured surfaces and were covered with an oxide layer of different color that made it possible to recognize and measure them under a microscope. It is obvious that it is not possible to make artificial cracks simulating the different shapes, sizes, locations, surface texture and combinations of different types that were seen in real parts used in this investigation.

Service-Induced vs Artificial Cracks

It is a common practice to use laboratory-grown fatigue cracks or EDM notches for instrument calibration or POD development. As mentioned above, service induced cracks in engine components are often covered with an oxide layer and are very tight due to residual stresses. These characteristics influence the inspection results for many NDI methods. A comparison of eddy current response between artificial and real cracks were made under the same experimental conditions and the EC signal magnitude was then plotted as a function of

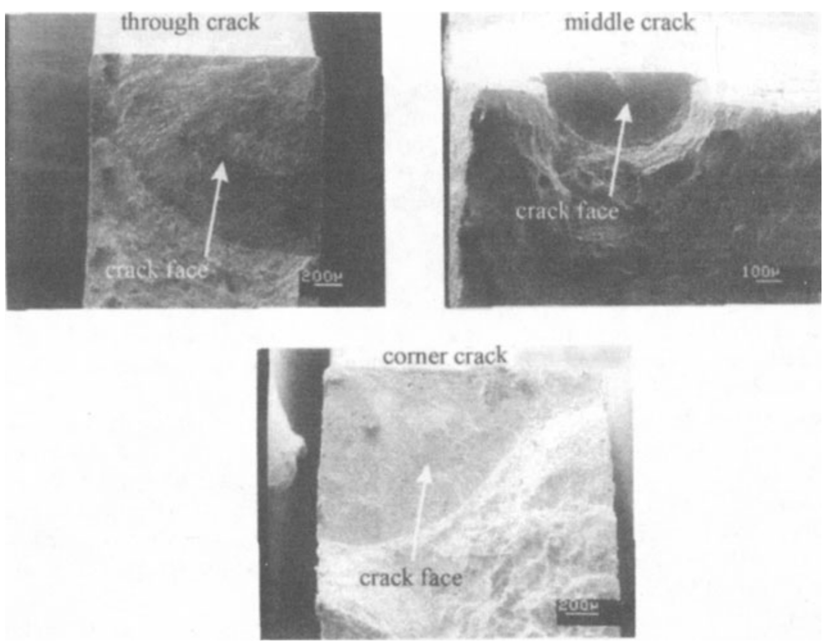

Figure 2. Scanning electron micrographs of different crack types found in bolt holes: through-, middle-, and corner-cracks.

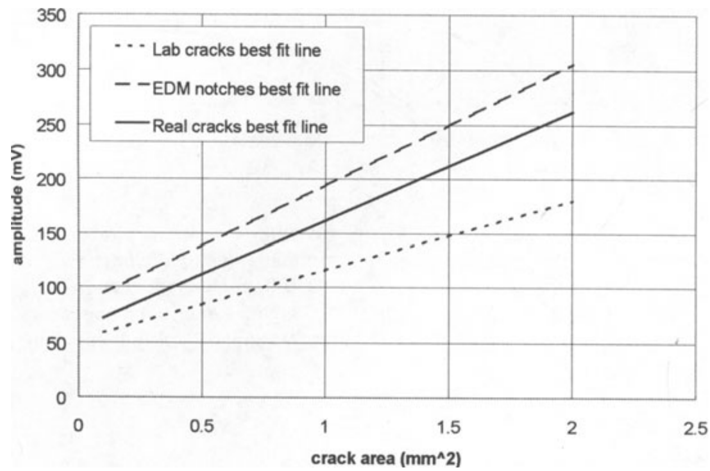

Figure 3. Eddy current signal amplitude for different flaw types.

the crack area. Despite scatter in the data for real cracks due to variations in the shape, type, location or orientation as well as coil position with respect to the crack and the bolt hole, a general trend appeared to exist. As shown in Figure 3, EDM slots generally produced EC signals 20% larger in magnitude from those of service-induced cracks and about 30-40% higher than the laboratory-grown fatigue cracks.

The higher signal amplitude in EDM notches is attributed to the wider gap between the two faces that provides a higher electrical insulation. Similarly, the oxide layer often present in real cracks act as an insulator resulting in a larger magnitude EC signal as compared to the laboratory grown cracks. Therefore, if EDM notches or fatigue cracks are employed for setting a detection limit for the instrument, these variations should be taken into account. Figure 3 also shows that the EC signal amplitude increases with increasing crack size for the three types of cracks in the size range investigated.

Probability of Detection

Table I contains a summary of the test results which compare the performance of the different NDI procedures used at the participating test sites and examples of probability of detection relationships to crack length are shown in Figure 4 for representative inspection methods used in this study. Despite the fact that the liquid penetrant inspections were carried out using the standard military procedures, significant variations were observed between the results from different sites. Such a variation is expected since the LPI method generally involves several steps that are very dependent on the operator. More importantly, the detection rate for all the LPI techniques investigated was alarmingly low for a technique most commonly used by the aircraft engine maintenance facilities. The crack tightness and oxidation as well as component surface condition may have contributed to missing a large number of small cracks and therefore the usefulness of this method for such applications is questionable. The 90/95% values for the LPI methods also varied widely and was the largest among the techniques investigated.

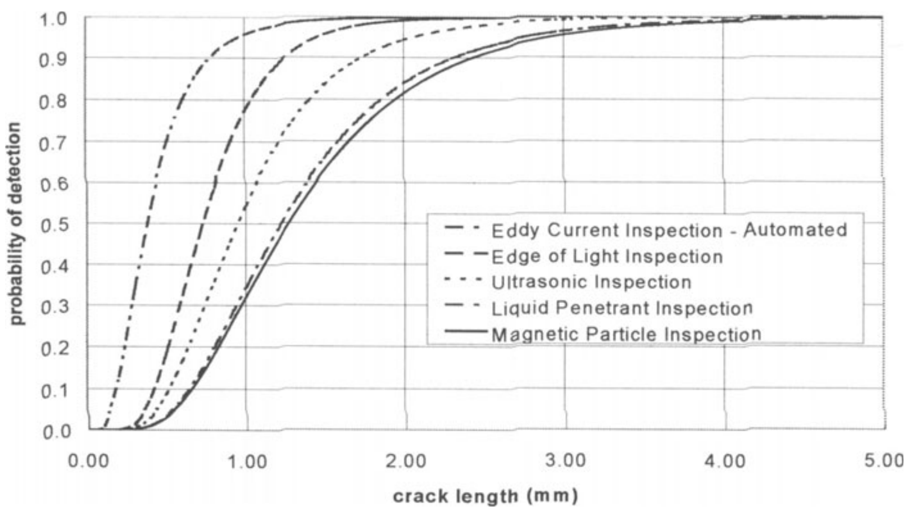

Figure 4. Examples of POD curves for different inspection techniques.

Table I. A summary of the results of different NDI procedures on bolt holes of J85-CAN40 compressor disks.

Technique	LPI	MPI	UTI	ECI-M		ECI-A		ECI-AP	EOL
Organization	A	D	A	A	C	A	B - 0.8	A	A
holes	296	372	372	381	381	381	381	381	328
cracks	246	311	311	320	320	320	320	320	281
hits	63	75	99	183	145	194	252	184	113
Rate (%)	26%	24%	32%	57%	45%	61%	79%	58%	40%
misses	183	236	212	137	175	126	68	136	168
Rate (%)	74%	76%	68%	43%	55%	39%	21%	43%	60%
False calls	2	8	1	2	0	1	9	1	2
Rate (%)	4%	13%	2%	3%	0%	2%	15%	2%	4%
90/95 length (mm)	2.59	2.76	1.90	0.84	1.11	0.65	0.51	0.87	1.37
Largest missed (mm)	2.10	2.04	1.30	0.99	1.00	0.89	4.69	1.00	1.26

Magnetic particle inspection was performed at only one facility that achieved a detection rate and 90/95% value similar to the LPI and those obtained in another study which involved two other organizations [8]. Ultrasonic surface wave inspections (UTI) were carried out using two different approaches. In one case, a contact wedge probe and manual inspection were used and in the other case an automated immersion C-scan system using leaky waves was employed [9]. The overall detection rates and the 90/95% values for both ultrasonic procedures were better then the LPI and MPI and the largest crack that was missed was smaller. Also, the new edge of light (EOL) technique [10] performed better than the conventional LPI and MPI and similar to the ultrasonic tests.

The detection rate for the manual eddy current inspection (ECI-M) was better than the LPI, MPI and ultrasonic techniques but clearly the automated eddy current (ECI-A) provided the best POD results among the technique investigated. The use of pattern recognition (ECI-AP) did not seem to improve the results. Also, it was apparent that the instrument settings such as the reject threshold level can substantially change the outcome of the automated systems. The use of high thresholds caused one inspection to miss a large crack, and at low thresholds the false call rate was high. Thus, the reject threshold level must be selected with care.

The data corresponding to the automated eddy current inspection with pattern recognition was further analyzed in order to determine the POD for the different crack types. As Figure 5 illustrates, through-cracks provide the best POD since they extend from one surface to another and therefore result in more interactions with the induced field of the EC probe. On the other hand, POD for corner- or middle-cracks was poor, as these cracks are generally smaller and more difficult to detect. Therefore, POD not only varies with the crack size but it is also dependent on the crack type. Artificial cracks made in the laboratory often simulate through-cracks that generally have higher POD than corner- or middle-cracks. However, the majority of service-induced cracks are corner-cracks. Therefore, the validity of POD data obtained using artificial cracks is questionable.

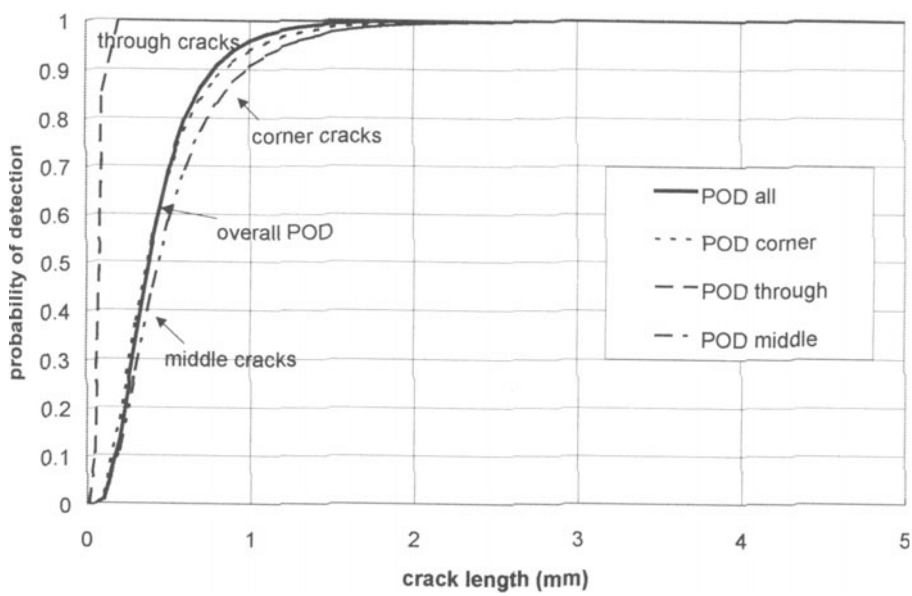

Figure 5. The POD for various crack types, using automated eddy current.

CONCLUSIONS

Among the techniques investigated, automated eddy current procedures had the highest sensitivity and reliability in detecting LCF cracks in the J85 CAN 40 engine components, as indicated by the POD-crack size relationships and the crack sizes detectable at 90% POD with 95% confidence. However, using very low thresholds resulted in high false calls and pattern recognition did not improve the detection rate or the 90/95% value. The results for the manual eddy current inspections were not as good as those of the automated systems but better than all the other techniques investigated. The edge of light and ultrasonic surface wave POD results also were inferior to the eddy current but better than the most commonly used liquid penetrant and magnetic particle inspections. LPI and MPI methods produced similar POD results on these components. Automated eddy current systems would be necessary if damage tolerance concepts are to be applied successfully.

NDI response from artificial cracks could be quite different from that of service-induced cracks due to shape, surface texture and tightness. Of the different crack types observed, through-cracks are much easier to detect and therefore give higher POD. Artificial cracks, in most cases, resemble the through-cracks. Most cracks in the investigated parts were corner-cracks that are difficult to simulate and detect. Therefore, for realistic POD measurements, actual parts with real service-induced cracks should be used if possible.

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