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Comparison of two non-destructive inspection techniques on the basis of sensitivity and reliability

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Abstract

Two non-destructive inspection (NDI) methods have been used to determine the damage tolerance life prediction of aero-engine turbine discs. For this purpose, low cycle fatigue cracks were examined in the compressor discs of tie bolt holes. The successful implementation of damage tolerance design method strongly depends on the sensitivity and reliability of applied NDI method.

The result of this study indicated that the manual eddy current inspection method is more sensitive and more reliable than the liquid penetrant inspection method in terms of detection of small cracks in the compressor discs.

Keywords: Liquid penetrant inspection; Eddy current inspection; Non-destructive inspection; Damage tolerance design

1. Introduction

Fracture control philosophies are used in the design and development and life prediction of stressed components. A common applied life prediction method is the 'Safe Life Prediction Method' [1]. However, most of the retired components (especially aircraft engine, such as discs and spacers) are not used in full capacity through the facilitation of the safe life prediction method. This is due to the fact that only few (e.g. 1 in 1000) components have developed a detectable crack size [2,3]. Due to the expensive maintenance costs for the safe life limit and its philosophy, an alternative design method has been developed to assure safe use of the components beyond the period of Safe Life Limit. Damage Tolerance philosophy forms the fundamentals of this design philosophy.

Damage tolerance is defined as the ability of a component to resist failure due to the presence of cracks or other defects for a specified period of usage. The damage tolerance design approach was first introduced by the United States Air Force (USAF) in 1970 and effectively applied since 1970 on a number of civil and military aircrafts [4]. According to this philosophy, all components contain flaws unlike the safe life prediction method.

By using routing inspections by non-destructive inspection (NDI) methods and probabilistic fracture mechanics predictions [5], the damage tolerance approach ensures that flaws will not grow to critical size during service. When the predetermined crack length limit is reached, there will be a risk of failure due to possible crack growth [6]. This predetermined crack length is known as 'Dysfunction Limit' and it is calculated by fracture mechanics analysis and safety factor as given by the engine manufacturers [4]. In the damage tolerance life approach, regular inspection may screen out components which have insufficient life to be returned to service.

The damage tolerance approach is used to calculate the number of hours (or cycles) to dysfunction. However, predictions are strongly influenced by initial and dysfunction crack length values used in the calculations. The

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dysfunction crack size is determined by using the estimates of service loads and material properties on the worst-case service conditions for a given component. On the other hand, the initial crack length depends strongly on the detection and the sizing capabilities of NDI technique used to inspect the components. The NDI technique requires to be quantified in terms of crack detection capabilities (sensitivity) and reliability (probability of detection) in order to establish the most suitable NDI technique for the use in damage tolerance life predictions [4].

The aim of this study is to determine the most suitable NDT method (i.e. eddy current inspection and liquid penetrant inspection) for damage tolerance based life prediction of aero-engine turbine discs in terms of degree of reliability and the level of sensitivity.

The probability of detection of NDI procedures can be assessed experimentally by inspecting statistically valid number of flawed and flaw-free parts.

2. Statistical analysis of NDI data

2.1. Probability of detection curve

Results of the NDI techniques used in this study consisted of three possibilities. A 'Hit' is when a crack exists and NDI technique identifies the crack. A 'Miss' is when a crack exists but the NDI technique does not detect it. A 'False Call' refers to the case when a crack does not exist but NDI method incorrectly indicates a crack. Hit or Miss Rates are defined as the number of cracks detected or missed over the total number of cracks present. False Call rate is the ratio of false calls to the total number of crack free sites. The inspection results were statistically evaluated considering the probability of detection (POD) as a function of crack size and the 95% lower confidence bound on POD curve.

Berens and Hovey [7] have grouped the experimental data into three categories which can be used to evaluate the reliability of NDI techniques.

Category 1: NDI sensitivity at one crack length (i.e. it is demonstrated that a NDI system is able to detect at least a given percentage of cracks at a certain length with a specified confidence limit.). *Category 2*: Estimation of POD with one inspection per crack (i.e. several components including a range of crack lengths are inspected once and then results are used to determine the POD as a function of crack length with confidence bounds. It is assumed that all cracks in specified interval have the same POD value). *Category 3*: Estimation of POD with multiple observations per crack (i.e. this method of collecting data provided an estimate of a POD for each individual crack. The most important factor of this experiment demonstrated that not all cracks of the same length have the same POD). In this study, on the basis of one inspection per crack (Category 2), 'Hit/Miss' type data are generated. Within such cases, the inspection results are better to be called probability of indication (POI) rather than POD, as the amount of false calls should be considered. The relationship between these variables can be indicated as the following example:

$$\mathrm{POI(a)} = p + \mathrm{POD(a)} - \mathrm{prob(false\ call\ and\ detection)}. \tag{1}$$

This states that POI is given by the sum of the false calls (p) and the correct indications POD, excluding the overlap. This equation can be rewritten as

$$\mathrm{POD(a)} = (\mathrm{POI(a)} - p)/(1 - p). \tag{2}$$

False call rate is undesirable and should be marginal because true probability of detection decreases with increasing false calls. False call is insensitive to crack length. Annis et al. [3] suggest a maximum false call rate of 5% to help ensure an accurate modeling of true POD. However, in this study, number of inspection data was not sufficient to determine true POD(a). High falls call rate (i.e. 9.1%), will affect the POD curve and, therefore, false call rate is ignored while evaluating the POD curve.

Berens and Hovey [7] have examined a number of distributions including Weibull, Probit, Logodds-linear scale, and log-logistic in order to determine the best analysis for the POD data. For detection probabilities of a given crack length, a linear regression analysis was carried out to determine the consistency of each distribution. Consistency was defined by Berens and Hovey [7] as the failure to reject the hypothesis at the 0.1 level of significance. It was proven that the log-logistic distribution yielded the best consistent POD data.

The functional form of the log-logistic distribution is as follows:

$$P_i = \frac{\exp(\beta_0 + \beta_1 \ln(a_i))}{1 + \exp(\beta_0 + \beta_1 \ln(a_i))}, \tag{3}$$

where P_i is the probability of detection; a_i the crack length; β_0 the location parameter; β_1 the slope parameter; $i = 1$, where n = total number of crack size intervals.

In order to determine the POD as a function of crack length for NDI data of category type 3, the a_i, P_i data pairs can be put into transformations as required by the analysis. However, for Category 2, the cracks need to be grouped into intervals of crack lengths. The grouping must be done according to the proportion of detection, assigned to a single crack length representative of the interval. Beren and Hovey [7] have suggested that the center of each interval would be more representative of the detection probability than the maximum crack length in that interval.

For linear regression of n pairs of a_i, P_i data points, the log-logistics transformation was performed by Beren and Hovey [7]

$$Y_i = \alpha + \beta X_i, \tag{4}$$

where $Y_i = \ln(P_i/(1 - P_\mathrm{i}))$ and $X_i = \ln(a_\mathrm{i})$; α and β are the intercept and slope which are found from the linear regression analysis. In cases where no cracks or all cracks are found, values for P_i are defined as $1/(n+1)$, $n/(n+1)$, respectively.