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Stochastic Reliability Risk Assessment Approaches

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ABSTRACT

Metal fatigue is insidious and constitutes for 90 % of all failures that are experienced in the field. Total life under fatigue comprises of the formation life and the propagation life. The distinction between formation life and propagation life is subjective. Pragmatically, the existence of inclusions, porosity and flaws prior to the component being put in to field could warrant the use of fracture mechanics approach to evaluate the fatigue life of a component.

In this paper, a probabilistic model to address variation in material property along with a response surface model to characterize flaw size is proposed.

KEYWORDS:

Probabilistic Design, Fracture Mechanics, Response Surface Model, DARWIN, Reliability, Risk Assessment.

INTRODUCTION

A study of field failure data or test data for a system or component would show that the time to failure is not a single deterministic value but spread over a range and yet the deterministic approach based design predict the life of a component to be a single deterministic value. This difference between the calculated life and that experienced in the field can be attributed to the randomness in the material property, loading conditions, environmental condition, manufacturing process variation etc. These uncertainties are accounted in the deterministic approach by using ‘margin of safety’ concept. The consequence of which is the design for unknown reliability, or conversely, design for unknown risk. With ever increasing demand for low cost products with an emphasis on the reliability, OEMs are faced with the challenge of designing components closer to the red line. Margin of safety based designs may not be viable under such circumstances.

In this paper, a probabilistic fatigue life model for compressor wheel failures that account for the material variation is proposed. In addition, a statistical approach for analyzing variation in duty cycle as well as a response surface model for characterizing flaw sizes is developed.

BACKGROUND

Compressor wheels used in turbochargers operate under a hostile environment. Compressor designs for commercial vehicles turbomachinery applications must be capable of sustaining speeds as high as 250,000 RPM, tip speed of 2000 Km / hr with up to 25g from engine vibrations. [1]

Two major modes of fatigue failures are observed in the compressor wheels [2].

- Low Cycle Fatigue (LCF) caused due to the change in the turbo speed, inducing hub, blade root or back disc failures in the compressor wheel.
- High Cycle Fatigue (HCF) caused due to the excitation of blade natural frequencies by turbo speed or due to rubbing, resulting in the blade failures.

In this paper, emphasis is on the LCF mode that results in either hub (Fig-1) or back disc failure (Fig-2)

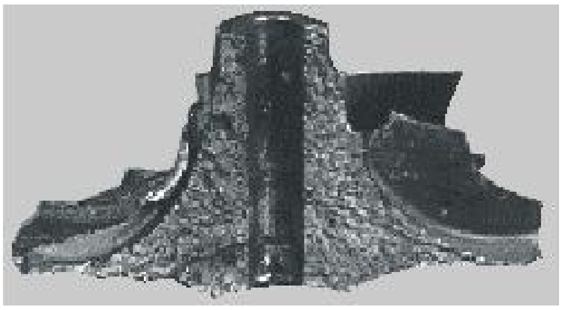

Figure 1 – Hub failure in compressor wheel

Figure 2 – Back disc failure in compressor wheel

PROBABILISTIC RELIABILITY RISK ASSESSMENT

Broadly, a probabilistic reliability risk assessment involves the following steps [3]:

1. Identify the potential failure modes in a component.
2. Specify / freeze the target reliability for each of the failure mode.
3. Establish the limit state function in terms of input Xs and response Y for each of the failure mode.
4. Identify the random variables and assign the corresponding statistical distribution to each of these random variables. Sensitivity analyses and DOE could be a good aid to identify the vital few variables.
5. Quantify the probability of failure using techniques such as FORM, SORM, Monte Carlo simulations and Response Surface Modeling.
6. Model system reliability in terms of its constituent component reliability.

FATIGUE CRACK GROWTH MODELING

Limit state function for the crack growth model is determined by using principles of Linear Elastic Fracture Mechanics. Fracture mechanics approach requires that an initial crack size be known or assumed. For components with imperfections or defects such as welding, porosities, casting defects an initial crack size is known. Alternatively, for an estimate of total fatigue life of a defect free material, fracture mechanics can be used to determine the propagation life and strain based approach to assess the formation life. The total life being sum of these two estimates [4]. In this analysis, initial flaw size was assumed to begin with and later it was validated with the metallurgical analysis.

Establishing Limit State Function

It is proposed that, the propagation life of the component be expressed in terms of the fracture toughness and parameters accounting for duty cycle variation. For these analyses, a probabilistic risk assessment code ‘Design Assessment of Reliability with Inspection’ - DARWIN from Southwest Research Institute is used extensively. [5]

Probabilistic risk assessment is carried out for the cast aluminum compressor wheel which is fitted for commercial vehicle turbo machinery applications as a methodology demonstration.

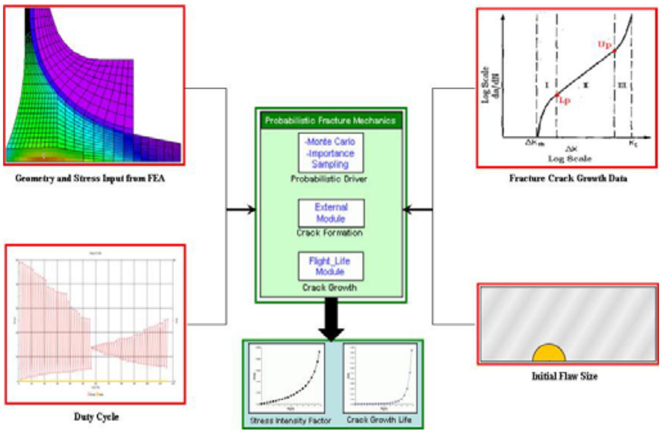

Figure 3 – Overall Approach for PDS

I. Analyses Setup: Based on the FEA geometry, general inherent 2D axisymmetric model is specified in DARWIN.

II. 2D anomaly size – Minimum flaw size from the metallurgical report is found to be 0.016” X 0.028” (Fig 4)

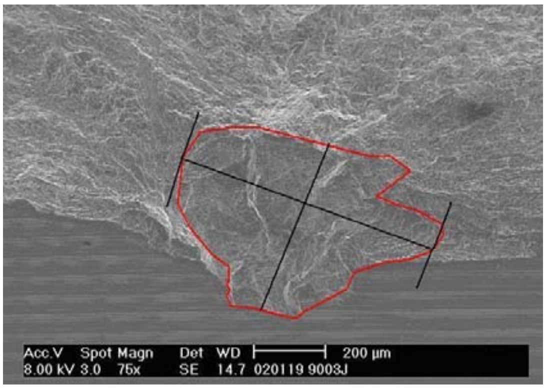

Figure 4 – Flaw Size from Metallurgical Report

III. Anomaly distribution – It typically involves defining an exceedance curve with defect size on the abscissa and the number of defects / million pounds along the ordinate. Characterizing the defect distribution for the aluminum material is beyond the scope of this paper. Instead, fatigue crack growth model is derived based on the assumption that the anomalies in the cast component would affect the threshold stress intensity and fracture toughness of the material.

IV. Material Properties: Fatigue crack growth data for C-354 material is estimated by using tensile stress - strain data based on the literature authored by Bahram Farahand & Kamaran Nikbin. [6]

Fatigue Crack Growth Properties: Calculated based on the 6% elongation at fracture for C354 material & fracture toughness of 18.5 units. (The value of C & K_{th} will change with a change in fracture toughness value.)

Material constant C = 7.924E-9
Strain hardening exponent n = 4.769
Threshold stress intensity:
$K_{th} = 1.537\ \text{KSI*In}^{0.5}$
Fracture toughness $K = 18.5\ \text{KSI*In}^{0.5}$

Newman crack closure equation is used in conjunction with the above properties.

$$\frac{da}{dN} = f\left[U_c \Delta K\right] \text{--------------------} \ (1)$$

$$U_c = \frac{\left(1 - \frac{\sigma_{open}}{\sigma_{\max}}\right)}{\left(1 - \frac{\sigma_{\min}}{\sigma_{\max}}\right)} \text{----------------} \ (2)$$

V. Zone Definition: One of the features of DARWIN software is that the component can be discretized in to zones of interest (Fig 5). To each of these zones finite elements can be assigned, crack type can be specified; anomaly distribution, POD and inspection schedules can be assigned. This will enable the user to compute the probability of failure for each of the zones as well as the percentage contribution of the zones to overall failure probability. For the current analyses, based on the available field data, the back disc region of the wheel is determined to be the weakest link and hence only one zone is defined on the back disc region of the compressor wheel.

VI. Mission (Duty Cycle): In general, duty cycle corresponds to repeating sequence of parameter such as turbo speed that characterizes the operating conditions of a turbocharger. Since, DARWIN cannot account for the speed sequence directly, maximum stress induced at various speed is calculated and is used for specifying the missions. For this analysis, duty cycle measurement recorded for bus application operating in Denver, New Orleans, Orange County and Cleveland geographies are used. Figure 6 shows post rain flow counted data for some geography.

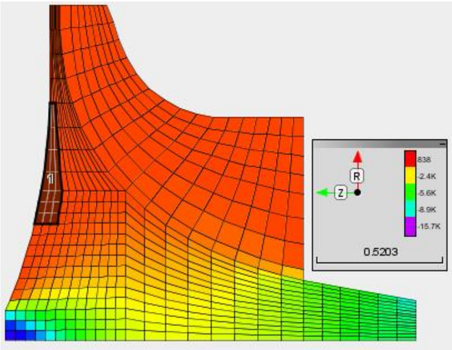

Figure 5 – Zone definition

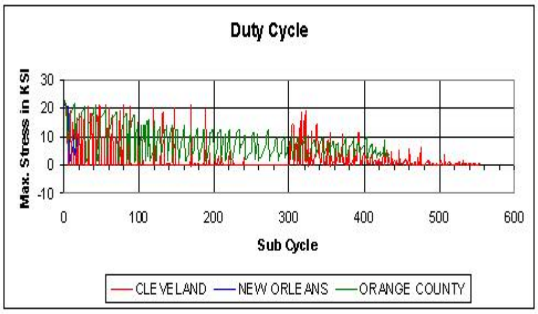

Figure 6 – Post Rain Flow Counted Duty Cycle Data

Response Surface Modeling

The qualifying tests carried out for compressor wheel uses a 3 point (min-max-min) duty cycle to evaluate the compressor wheel, as it is not possible to replicate the actual duty cycle in the gas stand testing. In order to model the response of life of the wheel with respect to the flaw size, stress levels corresponding to 38% - 100% -38% of the design speed of the turbocharger is used for the duty cycle input. Propagation life is estimated for various flaw sizes using DARWIN 6.0. The previous section provides the sequence of steps that were followed with an exception that 3 point duty cycle is being used instead of the actual duty cycle.

Based on this approach fatigue life for various flaw sizes have been determined & response surface is fitted to this result as shown in figure 7. Note that the analysis was terminated when failure did not occur after 250000 cycles. A full quadratic equation was fitted to evaluate the response (here fatigue life of the component) using MINITAB. Coefficients of the quadratic fit are as mentioned in table 1.

Coefficient	**Value**
Constant	5.76E+05
a	-1E+07
c	-1.5E+07
a*a	50989796
c*c	1.19E+08
a*c	1.62E+08

Table 1 – Coefficients of the quadratic fit

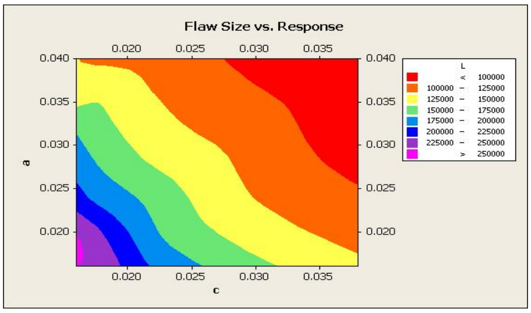

Figure 7 – Response Surface of Fatigue Life vs. Flaw Size

Modeling Variation in Duty Cycle & Material Property

Based on the test data used for calibrating the life prediction for compressor wheel, it has been observed that the variation in material property follows a Weibull distribution with a Weibull slope of 3. This is used as input in carrying out Monte Carlo simulations where in the variation in duty cycle has also been accounted for. To begin with a limit state function accounting for variation in fracture toughness value is developed. For this analyses the fracture toughness value is varied between 18.5 to 25 KSI*In$^{0.5}$ & for each of this value the life of the component is calculated. The entire process is repeated for various duty cycles. A statistical distribution is fitted to the observed variation in the calculated life. This variation together with the material variation is used for computing failure probability by Monte Carlo simulation.

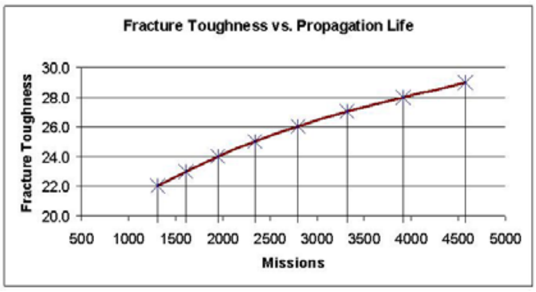

Figure 8 – Fracture Toughness vs. # of Missions

A power law equation of the form

$$L = A*(\Delta K)^B \text{ --- } (3)$$

can be fitted to the given data & using regression, values of A & B are determined such that we get $R^2 = 1$, that signifies the best fit.

It has been determined that the material variation follows a Weibull distribution with a Weibull slope of 3. Also based on the goodness of fit, it is observed that the variation in power law coefficients A & B follows a Normal distribution. Based on these distributions Monte Carlo simulations are carried out & the probability of failure for a particular case was estimated to be 0.0647 @ 9500 miles.

DISCUSSION & CONCLUSIONS

1. LEFM approach can be applied effectively to components that have inherent flaws & occlusions.
2. For components having micro cracks (<0.7 mm) life estimate based on LEFM approach is in good agreement with test data.
3. It is strongly recommended that fatigue Crack growth data be obtained from lab tests rather than using approximate values from a theoretical estimate.
4. Material properties, coefficients of the response surface, limit state function & probability of failure computed here in are indicative & are meant for academic interest only.

SCOPE FOR FUTURE WORK

1. As the real life duty cycle cannot be simulated in the gas stand testing, it is suggested that a simple 3 / 4 point stress cycle be developed such that the damage induced from this simple cycle is same as the damage caused from the actual duty cycle.
2. Variation in material properties is accounted with considerable accuracy however the same cannot be told for the variation in duty cycle. The issue gets further compounded due to the fact that the field return data does not capture the geography from where the failures were reported and hence the designer is at loss when it comes to determining the most severe duty cycle. In order to mitigate this it is suggested that a simulation algorithm be developed such that it can apportion the % contribution to failure from each of the geographies based on the cumulative Weibull Eta & Beta. Though this would be an approximation nevertheless it has a potential to give meaningful insight to the designer.
3. Integration of the crack formation and propagation module in to DARWIN such that total life can be estimated for all crack sizes irrespective of micro or macro cracks.

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