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Fatigue life estimation of aero engine mount structure using Monte Carlo simulation

Govindarajan Narayanan [a,*], Khosrow Rezaei [a], Udo Nackenhorst [b]

[a] Structures & Transmissions, Rolls Royce Deutschland Ltd & Co KG, Eschenweg 11, Dahlewitz, 15827 Blankenfelde-Mahlow, Germany
[b] Gottfried Wilhelm Leibniz Universitaet Hannover, Institute of Mechanics and Computational Mechanics, Hannover, Germany

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ABSTRACT

The estimation of fatigue life of mount structures in aero engine has become crucial for safe fly-home period in the event of a fan blade off situation since it has many random factors which will be influencing the durability of these structures either direct or indirect way. The imbalanced rotation during windmilling post fan blade off (FBO) creates vibratory loads of such low frequency but in high amplitude that leads to have the shorter fatigue life of these mount structures. Regression analysis during the evaluation of fatigue life under this circumstance provides the frequency of the front rotor shaft as most influencing parameter affecting the durability of the mount structures even though there are many other factors like, tribological conditions, material properties, impact fraction, environmental and thermal effects. Since it has low probability of occurrences but with high impact, the degree of conservatism in the estimated life is still hidden. Monte Carlo simulation of randomly selected lives from a predicted distribution of all dependent factors brings the variations in fatigue life of the mount structure. This can be estimated as a function of populated size. The mean and standard deviation of the simulated fatigue life converges with more number of randomly varied samples.

1. Introduction

Even if a product design has gone to maturity level, the design improvement process is essential in order to sustain in the challenging market. There are some incremental changes in product design which has been made so as to improve the performance, life, reliability, maintainability level and also to reduce the cost of manufacturing. Since the criticality of designed component increases the required level of confidence in generating the estimated fatigue life is also necessary. Hence it is not only that sound knowledge of fatigue and fracture of mount structure in aero engine is necessary but also knowledge in the influencing factors which are affecting the fatigue life is equally important. Fatigue life of material established from experimental is time consuming and costly. Conclusions regarding fatigue life are often inferred from a dangerously insufficient number of physical tests. Besides this diversity in fatigue life estimation, there are certain other factors which are not deterministic in nature.

In order to define the fatigue life of a mount structure of an aero engine, fatigue life of material has to be evaluated by experimentally with minimum sufficient number of samples at the same parameters. This is may not be possible in all the cases. With this connection, the fatigue life is often inferred from a statistically insufficient number of physical tests. The design of jet engines with high by-pass ratio demands to have not only larger size of fan but also heavier in weight. So as to ensure the aircraft and passenger safety the jet engine must be designed robustly to handle the situation like failed fan blades and core rotor blades. There are few literatures available which are dealing with the FBO situation of an aero engine [1–8]. There are many FBO events happened in aero engines with which there is no much information about the data related to the system unbalanced condition. The front structure handles major unbalanced fatigue load. This directly affects the fatigue load at the interfaces and mount structures. There is a necessity to study the variations involved in the fatigue load during the unbalanced situation of the rotor by the proposed stochastic approach which brings not only the variations involved in fatigue life cycles but also estimating the probability of failure events.

A generic way of designing against fatigue of structures is to use deterministic equations for strength and life. It is assumed that at loads below which calculated, there is no failure occurred. The calculated lives and load limits are usually coupled with a safety factor that is dictated by experience and design code requirements.

* Corresponding author. Tel.: +49 337 086 3808; fax: +49 337 086 3711.
E-mail addresses: Govindarajan.narayanan@rolls-royce.com, nggovind@gmail.com (G. Narayanan).

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More complication comes when the failure is extremely variable and dependent on many factors like material properties, processing method, and operating conditions. In such case, regression analysis will predict the most influencing parameters with which the fatigue life is estimated based on available inputs by Monte Carlo simulation. Reliability-based design simulations often use the Monte Carlo method as a sampling procedure for predicting failure. The combination of designing for very small failure probabilities ($\sim 10^{-8}$–10^{-6}) and using computationally expensive finite element models, makes Monte Carlo simulations very costly [5,6]. The probability of failure estimation has been done based on the Monte Carlo simulation on various influencing parameter which directly affects the fatigue life of mount structure. Monte Carlo simulation is introduced in estimating the fatigue life of mount structure for two main reasons: limited sampling of computationally expensive finite element solutions and to handle the diversified nature of many influencing factors of windmilling load post fan blade off situation.

Current new requirement on windmilling specification is quite challenging to achieve and additionally we are in lack of having robust methods to address it. With predicted conservative transient loads (e.g. Fan Blade Off load cases), the structural designs are always in non-optimum way and even sometimes difficult to achieve the required specifications. The conventional approach so far used is to refer the available FBO test data which is quite challenging often when there is no relevant test data available.

The proposed method predicts the anomalies involved in the load predictions and provide the scatterings in to the load values during the FBO event. This stochastic approach in evaluating windmilling load includes the variations involved in the load predictions and also brings maximum likelihood of the worst load case. This gives more light on the structural reliability and durability. The load predicted by Monte Carlo simulation method not only gives the sensitivity on the load but also probability of failure on maximum load on the structure. The mean and standard deviation of the transient load along with the variations is produced by random samples.

It accumulates all the relevant factors involved in realistic condition after fan blade off event in an aero engine. The proposed method generate random samples in a given predicted probability density function and by crude sample Monte Carlo techniques, which is most efficient than hit or miss method. The predicted load from transient dynamic analysis alone will not be sufficient enough to produce structural integrity statement. The sensitivity in load prediction under the transient condition brings more clarity to have efficient design.

2. Motivation of the problem

As long as the fan blades are within the shaft alignment, there will not be any additional loads other than the normal flight loads. In the one blade off situation, the other fan blades start to rub heavily with the casings structure and also an imbalance force is generated by shifting of centre of gravity of the shaft and thereby produces local unbalanced force which subsequently generates fluctuating contact loads in the bearing outer race to the bearing support structures. Depends on the size of the fan blades, imbalance load and fly home period, the engine mount structures may experience variable amplitude fatigue loads. During this windmilling post FBO situation, the fatigue life estimation depends on many parameters:

Evaluation of the load.
Tribological behaviour of the system post FBO impact.
Coupling effect between the shaft/disc vibration and mistuning.
Thermal effects – due to rubbing.
Non symmetrical inertia.
Aerodynamic cross coupling effect.
Jumping phenomenon of dynamic response of the structures.
Variation in system stiffness of the system post FBO impact.
Amount of impact to the fan blade.

In over all the probability of FBO event presumed to be 10^{-7}–10^{-8} per engine flight hour [5]. In such a scenario of high impact with low probability events, the chain of conservatives in evaluation of fatigue life of mount structure is inevitable. The effect of such conservatism in fatigue life of mount structure leads to either over designing or not meeting the criterion. In order to have optimum design probabilistic analysis with Monte Carlo simulation technique is involved in the fatigue life estimation of mount structure of aero engine for the transient load cases.

The mount structure in aero engine has to have enough fatigue life in order to meet the required structural integrity level. The most influencing parameters which are affecting the fatigue life of mount structure are estimated as the frequency of the LP rotor shaft which decides the amount of load which is getting transferred to the mount structure. This paper considers all the relevant factors which are influencing the fatigue life of mount structures along with the distribution behaviour of individual parameters. Regression analysis has also been performed in order to explain the relationship between all the parameters. Then for the predicted distribution, using Monte Carlo technique, many sample sizes have been decided in order to achieve convergence in fatigue life of mount structure.

Fig. 1 shows typical aero engine and bearing mount structure which is mounted in behind the fan blades.

3. Probability of failure estimates

The probability of failure is generally estimated using a limit state function, G which defines the failure condition. The response (stress or load) limit state function is assumed to be functions of statistically independent random variables of X_1, X_2, $\ldots X_n$. Similarly the limit state function of capacity (fatigue strength) is assumed to be a set of independent random variables of Y_1, Y_2, $\ldots Y_n$. These independent random variables are generated based on the available raw data of predicted probability density function.

$$G(X_i,\ Y_i) = R(X_1,\ X_2, \ldots X_n) - C(Y_1,\ Y_2, \ldots Y_n) \tag{1}$$

Fatigue failure occurs when $G \geqslant 0$ and the structure is safe when $G < 0$. In general case, the capacity and response of the limit state cannot be explicitly separated as in Eq. (1). The general form of probability of failure is observed in Eq. (2) for the limit state function is less than zero [9–12].

$$p_f = \int f_G(G)\, dG \tag{2}$$

where $f_G\ (G)$ is the probability density function (PDF) of the limit state function G.

Sampling procedures are commonly used to estimate probability of failure in reliability-based structural design. For estimating very low probabilities the number of required samples can be high, and is expressed as the difference of two functions of independent sets of random variables (e.g., capacity minus response). First the cumulative distribution function (CDF) of one of the function created by sampling one set of random variables, and then the probability of failure is obtained by sampling the other set of variables using the CDF constructed in the first phase.