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# Helicopter blade reliability: Statistical data analysis and modeling

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ABSTRACT

The concept of reliability has been attracting attentions in mechanical engineering following the developments of the aerospace industries. Limited failure data and statistical analyses of helicopter components reliability exist in the technical literature. For filling this gap, a nonparametric analysis is conducted on the performance of the 338 blades of some Iranian helicopters, which were in service between 1974 and 2012. These blades have 41 different failure modes. In this paper, statistical reliability analysis is conducted based on two strategies: In strategy I, general failure is defined as scrapping or retirement of the blade. In strategy II, the blade is assumed to be subjected to different modes of failure and the cumulative mode-specific functions are derived for each failure modes using Nelson–Aalen estimator. The Kaplan–Meier estimator is used for calculating the nonparametric reliability functions. Confidence intervals are derived for the reliability results and parametric fits are conducted using the maximum likelihood estimation. An important result from parametric analysis is that the blade reliability has a 3-parameter Weibull distribution and so the blades exhibit an increasing failure rate. Finally, considering the mode-specific hazard functions, the failure mode 1, i.e., excessive vibration is observed to have major contribution to the blade failures.

## 1. Introduction

The growing trends of the application of the concept of reliability in mechanical engineering design owe to the statistical nature of the various failure modes of the mechanical components. It is essential that the mechanical equipment operate reliably under all the conditions in which it is used; however, the requirement for reliability is different for each application. Reliability is the probability that a component, equipment, or system will perform a required function under the operating conditions encountered for a stated period of time [1]. There are many different operational requirements and various environments, thus reliability is quantified in many different ways. One of them is the statistical analysis that is referred to as lifetime, survival time, or failure time data. Some methods of dealing with lifetime data are quite old, but starting at about 1970 the field expanded rapidly with respect to methodology, theory, and fields of applications [2].

Limited failure data and statistical analyses of helicopter components reliability exist in the technical literature and few statistical studies were made to model the reliability of these parts. Bell Helicopters Company documented the reliability for some OH-58D components using the strength/load interaction formulation and established a life versus reliability relationship [3]. Sometimes there is a single lifetime for each individual, but failure may be of different modes of types. Often the modes refer to cause of failure, in which case the term "competing risks" or "multiple modes of failure" is sometimes used [2]. There have been many efforts to consider failure mechanisms (competing risks) for each component to analyze reliability [4–6]. Kaplan and Meier [7] presented the Kaplan–Meier estimator for calculating the nonparametric reliability function. In the nonparametric analysis, the confidence intervals are derived to inform about the dispersion around the nonparametric reliability function [8,9]. Nelson and Aalen presented the Nelson–Aalen estimator for calculating the cumulative mode-specific functions for each failure modes [10–13].

In this paper, failure data are collected for 338 helicopter blades. These blades have 41 different failure modes. Two different strategies are adopted. In the first one, general failure is defined as scrapping of the blade, which results in retirement of the blade. A nonparametric analysis of blade reliability is conducted for 338 blades, which were in service between 1974 and 2012. Because in this case the dataset is censored due to the fact that some of the blades are still operational at the end of gathering data, the Kaplan–Meier estimator is used for calculating the blade reliability function. In addition, confidence intervals are derived for the nonparametric reliability result. In the second strategy, the blade is

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**Table 1**
Data collection template and sample data for statistical analysis of blade reliability.

| Failure mode | Failure date | Mode of failure | Flight times (hours) |
|---|---|---|---|
| 1 | 8/10/2002 | Excessive Vibration | 683 |
| 2 | 27/2/1985 | Corroded | 746 |
| 3 | 15/12/1982 | Chipped | 1204 |
| 4 | 30/12/1975 | Cracked | 603 |
| 5 | 12/8/1985 | Bent/Dented | 719 |
| 6 | 23/8/1998 | Scrapping | 1108 |
| 7 | 7/9/1999 | Hard Landing | 90 |
| 8 | 28/7/1976 | Sudden Stop | 1413 |
| 10 | 4/5/1982 | Worn Excessively | 1501 |
| 17 | 11/7/1978 | Delaminated | 1155 |

assumed to be subjected to different modes of failure. In the other words, causes other than scrapping such as fatigue, excessive vibration, corrosion, ... can also make the blade to fail. So, the blade is faced with multiple modes of failure in this strategy. In this case, the dataset is unsensored because the first time failures of the blades are available. A nonparametric analysis of blade reliability is conducted using the Kaplan–Meier estimator [7] and the confidence intervals are derived for the nonparametric reliability result. In addition, the cumulative mode-specific functions are derived for each failure modes by using Nelson–Aalen estimator. In both cases, parametric fits are conducted using the maximum likelihood estimation (MLE) and graphical approach. Moreover, the goodness of fit tests are used to justify the choice of a 3-parameter Weibull distribution for modeling blade reliability and then with the maximum likelihood estimation, the parameters of the 3-parameter Weibull distribution are calculated.

Applying the MLE procedure, the values of the shape parameter ($\beta = 1.793$) and the scale parameter ($\theta = 9390.97$ hours) are derived for the first strategy, and the values of the shape parameter ($\beta = 2.187$) and the scale parameter ($\theta = 1234.9$ hours) are derived for the second one. It is seen that the shape parameter $\beta$ is greater than one in both strategies. Consequently, the helicopter blades in both cases (strategies I and II) suffer increasing failure rate or wear-out failures and as a result their failure probability of occurrence increases over time. Hence, with regarding the bathtub hazard rate curve their expected average life in wear-out period of life can be much smaller than their mean life in the period of their useful life.

## 2. Dataset description

For the purpose of this study, the data taken from the Iranian helicopter industry (PANHA) are used. This dataset provides extensive data on helicopter blade failures, as well as flight and in service histories since 1974.

For each blade in dataset, these data are collected from the dataset: (1) its flight times; (2) its failure date, if failure occurred; (3) the failure mode according to each flight time; and (4) the "censored time," if no failure occurred. This last point is further explained in the following section where data censoring and the Kaplan–Meier estimator are discussed. The data collection template and sample data for this analysis for the most important failure modes are shown in Table 1. In the following section, the data are collected to conduct a nonparametric reliability analysis of all the blades identified previously.

## 3. Nonparametric reliability analysis of helicopter blade

Two different reliability analyses are accomplished:

Strategy I: General failure is defined as scrapping or retirement of the blade.

Strategy II: Failure of the blade occurs as a result of different modes of failure.

In the second strategy, failure does not mean the retirement of the blade. In fact, the distinction of the two strategies is that the first one accounts for the repairments done on the blades and as a result the repaired blade can be treated as a new one. The retirement of the blades in this strategy occurs when the repairments can no longer be helpful and so, the blade has to be scrapped. However, the second strategy considers that the blade stops to work properly when each of the failure modes occur.

### 3.1. *Censored data sample and Kaplan–Meier estimator as applied in the context of the first strategy*

Censoring occurs when life data for statistical analysis of a set of items is incomplete, as in the case the dataset corresponding to the first strategy. More specifically, right censoring occurs. This means the following: (1) the blades in the present dataset are activated at different points in time but all these activation times in this dataset are known, (2) failure dates and censoring are stochastic, and (3) censoring occurs because the blade is still operational at the end of gathering data. In this work, the powerful Kaplan–Meier estimator [7] is adopted, which is best suited for handling the type of censoring in the present dataset. The Kaplan–Meier estimator of the reliability function with censored data is given by:

$$\hat{R}(t) = \prod_{\textit{all i such that } t_{(i)} \le t} \frac{n_i - d_i}{n_i} \tag{1}$$

where:

$$\begin{aligned} &t_{(i)}\text{: time to the i'th failure (arranged in ascending order)} \\ &n_i = \text{number of operational units right before } t_{(i)} \\ &\quad = n - [\text{number of censored units right before } t_{(i)}] \\ &\qquad - [\text{number of failed units right before } t_{(i)}] \\ &d_i = \text{number of failure units at } t_{(i)} \end{aligned} \tag{2}$$

### 3.2. *Confidence interval analysis*

The Kaplan–Meier estimator (Eq. (1)) provides a maximum likelihood estimate of reliability but does not inform about the dispersion around $\hat{R}(t_i)$. This dispersion is captured by the variance or standard deviation of the estimator, which is then used to derive the upper and lower bounds for say a 95% confidence interval (that is, a 95% likelihood that the actual reliability will fall between the two calculated bounds, with the Kaplan–Meier analysis providing us with the most likely estimate). The variance of the estimator is provided by Greenwood's formula [8] and [9]:

$$\operatorname{var}\left[R(t_i)\right] \equiv \sigma^2(t_i) = \left[\hat{R}(t_i)\right]^2 \sum_{j \le i} \frac{d_j}{n_j(n_j - d_j)} \tag{3}$$

Moreover, the 95% confidence interval is determined by:

$$R_{95\%} = \hat{R}(t_i) \pm 1.96\sigma(t_i) \tag{4}$$

More details about these equations can be found in [8] and [9].

### 3.3. *Kaplan plot of blade reliability in presence of censored data*

With the brief overview of censoring, of the Kaplan–Meier estimator, and of confidence intervals, the blade reliability can be analyzed from the present dataset. According to the first strategy for the 338 blades analyzed, 310 censored and 28 failure times are obtained. The data is treated with the Kaplan–Meier estimator (Eq. (1)), and the Kaplan–Meier plot of the reliability of helicopter