Reliability Analysis of Aircraft Air Conditioning Packs

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Abstract

Air conditioning packs of aircraft are subject to a number of failures like other aircraft components. However, the number and results of unexpected failures in the Kingdom are expected to be more severe than the corresponding failures in many other countries due to climatic conditions. This paper examines the time-to failure distribution of Boeing 737 air conditioning packs by using Weibull method which is one of the most useful tools in aerospace system reliability analysis. Forecasting of part failure rates are very important for maintenance planning since it allows for predicting the future failures and determining the overhaul period or scheduled inspection period at an acceptable probability of failure.

I. Introduction

Air conditioning unit is an important system in an aircraft which is used to:

- Maintain a comfortable cabin temperature throughout al conditions of flight
- Control cabin humidity to assure passenger comfort
- Prevent window fogging
- Provide cooling for avionics

These units are also subjected to variety of failures like any other aircraft components. The unscheduled maintenance which results from unexpected failure is the main concern of the maintenance organizations. Unscheduled maintenance may cause delay and cancellations and can easily wipe out the profit of an airline. Thus predictions about failure characteristics of various components will be very useful for decision makers for planning preventive maintenance and/or replacement programs that minimizes the unscheduled maintenance. In this study, the reliability and failure characteristics of aircraft air conditioning packs are investigated by using the Weibull model and expected number of unscheduled maintenance actions is estimated.

II. The Weibull Model

The reliability $R(t)$ of air conditioning pack is defined as the probability that it will function over some period of time t. To express this relationship mathematically a continuous random variable T is defined to be the time to failure of the component; $T \geq 0$.Then, reliability can be written as $P[T>t]=R(t)$. In general terms, reliability can be expressed as [4]

$$R(t) = \exp\left[-\int_0^t \lambda(t)\,dt\right] \quad (1)$$

where :
$\lambda(t)$= Failure rate
t = Flight time in hours

The Weibull model is characterized by a failure rate function in the following form:

$$\lambda(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \qquad \beta > 0, \eta > 0, \ t \geq 0$$

(2)

Using this failure rate function, equation (1) will represent a well-known two-parameter Weibull model as follows:

$$R(t) = \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \tag{3}$$

Often the complementary function to the reliability function is used, $F(t)= 1-R(t)$.The complementary function is also known as cumulative distribution function and can be expressed in the following manner:

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \tag{4}$$

Beta (β) is referred to as the shape parameter and indicates which class of failures is present:

- β<1.0 indicates that the product has a decreasing failure rate (infant mortality)
- β=1.0 means random failures (independent of age)
- β>1.0 indicates an increasing failure rate (wearout failures)

The Weibull characteristic life, called eta (η), is a measure of the scale, or spread, in the distribution of data.

Whenever there is a minimum life t_0, the three-parameter Weibull model may be appropriate. This distribution assumes that no failure will take place prior to time t_0. For this distribution[4],

$$R(t) = \exp\left[-\left(\frac{t - t_0}{\eta}\right)^{\beta}\right] \qquad t>t_0 \tag{5}$$

$$\lambda(t) = \frac{\beta}{\eta}\left(\frac{t - t_0}{\eta}\right)^{\beta-1} \qquad t>t_0 \tag{6}$$

$$F(t) = 1 - \exp\left[-\left(\frac{t - t_0}{\eta}\right)^{\beta}\right] \quad t>t_0 \tag{7}$$

III. Application of the Weibull Model to Failure Data

Various approaches commonly used in fitting the Weibull model to the failure data. In the present study, a straightforward Excel-based analysis was used. The approach is explained below [1,2,3].

From equation (4), following can be written

$$\ln[1 - F(t)] = -\left(\frac{t}{\eta}\right)^{\beta}$$

and

$$\ln\left\{\ln\left[\frac{1}{1 - F(t)}\right]\right\} = \beta \ln(t) - \beta \ln(\eta) \tag{8}$$

Thus, the equation is now in the form of a linear equation $y= mx + c$. The cumulative failure distribution function $F(t)$ can be substituted by its estimate $F(t_i)$ using median rank formula[4] :

$$F(t_i) = \frac{i}{N + 1} \quad 0 \le i \le N \tag{9}$$

It can be seen that β corresponds to the slope and β lnη is the intercept in equation (8). By performing the linear regression analysis using equation (8), the parameters β and η can be determined. For three-parameter Weibull model t_0 should be known.Its value is to be adjusted within the range $0.65t_{min} < t_0 < t_{min}$, until a good fit is obtained, where t_{min} is the minimum failure time in the data.

IV. Reliability Analysis of Air Conditioning Packs Failure Data

In this part, a group of data obtained from a local aviation facility is to be analyzed. Data represent the time to failure of two air conditioning packs on Boeing 737-700 aircraft over a period of three years. Each datum corresponds to the removal or inspection of the component due to some reported fault. The ages at removal are measured in terms of flying hours. The data do not include any planned removals or censored data. It should also be noted that the random variable under consideration is time to removal and not time to failure. Although the components are removed based on some fault reporting, one cannot say that the component that was removed actually caused the fault. It is also assumed that after removal, the component is restored to its original condition, or "as good as new."

The analysis is carried out by using both two-parameter Weibull model and three-parameter Weibull model and summary of the results is given in Table 1.

Parameter	**Two-parameter Weibull Model**	**Three-parameter Weibull Model**
Sample size, *N*	27	27
Minimum life (t_0), hours	0.0	9.18
Characteristics life,η (hours)	121.54	104.21
Shape parameter, β	0.9979	0.8249
Index of fit, R	0.9438	0.9718
Coefficient of determination (R^2)	0.8907	0.9445

Table 1. Summary of Weibull analysis results

It should be noted that certain criteria should be met before implementing the three-parameter Weibull model :

- There should be physical explanation of why failures cannot occur before t_0
- A sample size should be greater than 15 (preferably 20)
- The index of fit should increase significantly

Analysis of the air conditioning packs reveals the following characteristics with respect to stated criteria.

- The failures do not occur before t_0.
- The sample size is 27.
- The index of fit R, increases from 0.9438 to 0.9718.Additionally the coefficient of determination R^2, another measure of goodness of fit, increases from 0.8907 to 0.9445.

Since three-parameter Weibull model provides a better fit to data, this model is accepted. The result of analysis for three-parameter Weibull model is shown in Table 2 and Fig. 1. Following can be said about the Weibull parameters:

- Minimum life t_0 = 9.18 hours
- Scale parameter is 104.21 hours, which indicates that about 63 percent of removals happened up to that time.
- Shape parameter is less than one (β<1), which reflects a decreasing failure rate (infant mortality) of air conditioning packs as it is indicated in Fig.2. The result indicates that one may have a 95 % confidence that $0.7465 \leq \beta \leq 0.9032$.

i	***t-t0*** **(hr)**	***F*(*t*) = *i*/(*N*+1)**	**Z=1/(1-*F*(*t*))**	**Ln (Ln Z)**	**ln (*t*)**
1	3.93	0.035714	1.037037	-3.314076	1.368639
2	5.21	0.071429	1.076923	-2.602232	1.650580
3	5.59	0.107143	1.120000	-2.177463	1.720979
4	19.49	0.142857	1.166667	-1.869825	2.969902
5	23.02	0.178571	1.217391	-1.626023	3.136363
6	24.67	0.214286	1.272727	-1.422286	3.205588
7	24.72	0.250000	1.333333	-1.245899	3.207613
8	26.26	0.285714	1.400000	-1.089240	3.268047
9	27.17	0.321429	1.473684	-0.947354	3.302113
10	29.94	0.357143	1.555556	-0.816824	3.399195
11	32.30	0.392857	1.647059	-0.695167	3.475067
12	36.53	0.428571	1.750000	-0.580505	3.598134
13	36.74	0.464286	1.866667	-0.471358	3.603866
14	41.34	0.500000	2.000000	-0.366513	3.721831
15	56.14	0.535714	2.153846	-0.264936	4.027849
16	63.64	0.571429	2.333333	-0.165703	4.153242
17	74.70	0.607143	2.545455	-0.067948	4.313480
18	92.25	0.642857	2.800000	0.029189	4.524502
19	112.53	0.678571	3.111111	0.126615	4.723220
20	158.84	0.714286	3.500000	0.225351	5.067897
21	165.48	0.750000	4.000000	0.326634	5.108850
22	188.24	0.785714	4.666667	0.432071	5.237718
23	211.74	0.821429	5.600000	0.543931	5.355359
24	261.55	0.857143	7.000000	0.665730	5.566625
25	287.87	0.892857	9.333333	0.803611	5.662509
26	520.38	0.928571	14.000000	0.970422	6.254559
27	590.40	0.964286	28.000000	1.203634	6.380800

Regression Statistics	
R (index of fit)	0.971877
R Square	0.944545
Adjusted R Square	0.942327
Standard Error	0.269331
Observations	27

Table 2. Failure data analysis of air conditioning pack

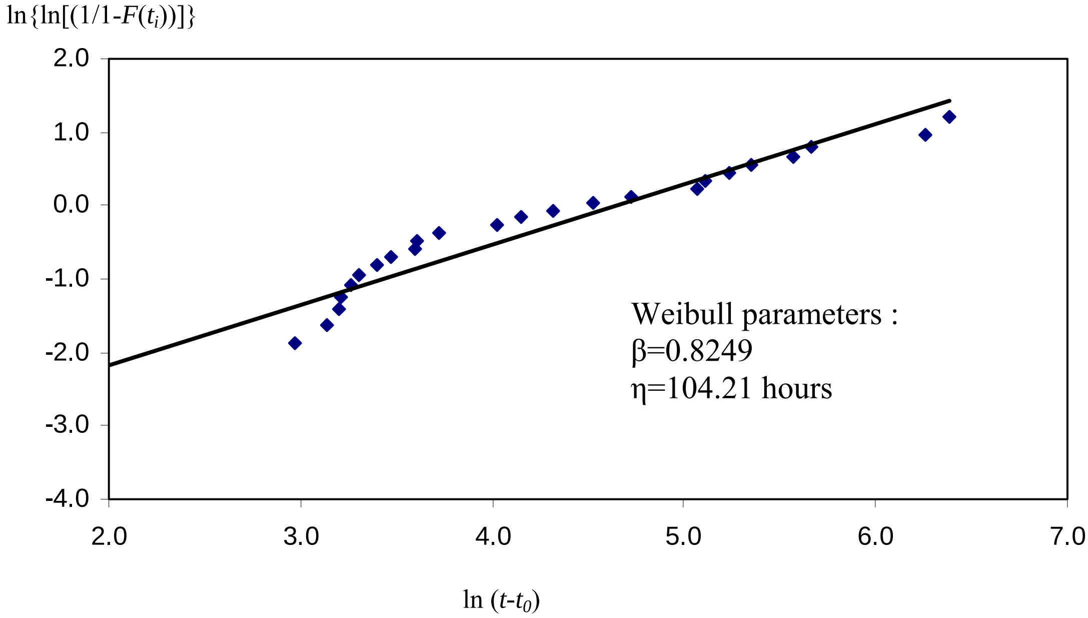

Fig.1. The Weibull plot for the failure data in hours of air conditioning packs

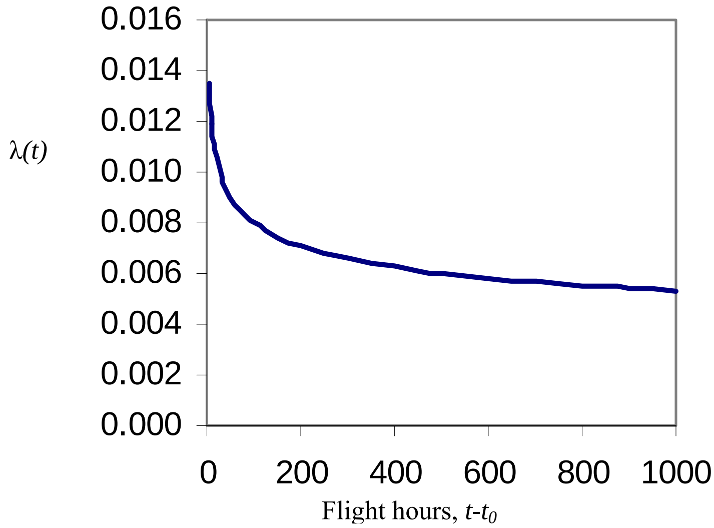

Fig.2. Estimated failure rate over time

V. Expected Number of Unscheduled Maintenance Actions

The expected number of removals *m(t)*, for an operating period of *T* hours can be described by the following equation [4]:

$$m(t) = \frac{\mathrm{T}}{\mathrm{MTTF}} \tag{10}$$

where:

T= period of time under consideration (in flight hours)
MTTF = Mean time to failure

The mean time to failure (MTTF) of the Weibull distribution can be calculated by using the equation given below [6]:

$$\mathrm{MTTF} = \eta\Gamma\left(1+\frac{1}{\beta}\right)$$

where $\Gamma(x)$ is the gamma function.

For air conditioning packs under consideration, MTTF = 115.45 hours. Hence, the estimated number of unscheduled maintenance actions (removals) per year (approximately 1200 flying hours) for the air conditioning pack can be calculated as *m(1200)*=10 from equation (10).This number also represents 10 potential delays/cancellations due to air conditioning packs for each aircraft. This is relatively high number considering the fact that a modern jet aircraft has up to 135, 000 unique components[5].

VI. No fault Found (NFF)

No fault found (NFF), is basically a reported fault for which subsequently no cause can be found. Isolating the true cause of failure of a complex system demands a great amount of skill and if the technical skill cannot resolve a failure to a single unit, then the probability of making errors of judgment will increase. This problem is general for all airlines. A Boeing figure of 40% is quoted for incorrect part removals from airframes, and British Airways estimates that NFF cost them on the order of £20 million per annum[5]. For the air conditioning packs it is found out that 9% of removals are NFF.

VII. Conclusion

The Weibull analysis is an effective tool for failure forecasts and analysis of the various aircraft parts and systems, and extremely useful for maintenance planning, particularly reliability centered maintenance. In this case, the failure characteristics of aircraft air conditioning packs have been analyzed by using Excel program. The good straight line fit to the transformed data supports the validity of the Weibull model. The resulting parameter β was found as less than 1, indicating that a planned replacement policy is not cost effective for this component. The causes of $\beta<1$, may be improper use, improper installation and setup, insufficient quality control, and defective materials.

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Nomenclature

$\lambda(t)$ = Failure rate function

$R(t)$ = Reliability function

$F(t)$ = Cumulative distribution function

t = Operation time in flight hours

t_0 = Minimum life

β,η = Weibull parameters

N = Number of observations

MTTF = Mean time to failure

$m(t)$ = Expected number of removals