EVALUATION AND RELIABILITY ANALYSIS OF AN ELECTRIC ALTIMETER- A CASE STUDY

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Abstract

An electric altimeter is a flight-critical component of aircraft instrumentation that indicates aircraft altitude. A domestic airline recently witnessed significant failures of this critical component in its Boeing 737 fleet leading to flight delays, unscheduled maintenance and disruptions of service. The objective of this study is to conduct a reliability study to understand and analyze the root cause of electric altimeter failures, and determine its performance capability. In order to understand the nature of failures, a Fault Tree Analysis (FTA) is performed that identifies the potential causes of failures of this flight-critical component. During the course of this research, significant data-gathering and analysis efforts were carried out leading to a systematic evaluation of the component under consideration. The approach to estimate the electric altimeter reliability utilized operational failures that reflected the actual aircraft-operating environment over ten years. Information on component failures was obtained from the aircraft logbooks. The distribution that best described the failure processes was a two-parameter Weibull distribution. The mean time between failures (MTBF) was computed and compared against the current fleet-wide MTBF rate. Based on the reliability and root-cause analysis, airline operators can develop preventive maintenance procedures that would help minimize the failures of reworked electric altimeters. It is anticipated that this study would provide a methodology for future reliability studies leading to systematic testing and evaluation procedures for flight-critical avionic components.

Introduction

Using the statistical tools for product-life data analysis, reliability engineers can determine the probability and durability of parts, components, and systems to perform their required functions for the desired life span without failure. The product-life data can be measured in hours, miles, cycles-to-failure, stress cycles, or any other metric with which the life or exposure of the product can be measured. In the early reliability studies with electronic components, it was found that early failures (or infant mortalities) occurred frequently. Over time, the population exhibited a constant failure rate. It was also observed that some devices would finally reach a threshold in their operating life where the failure rate would again increase sharply, and aging or wear-out mechanisms would dominate and cause rapid failure of the surviving population as shown in Figure 1.

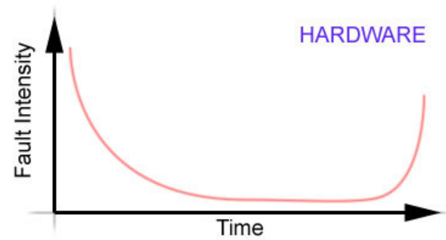


Figure 1. Fault intensity vs. time [1]

Engineers in the non-electronic world picked up on this research finding and used it as a basis for developing maintenance strategies. Reliability Engineering [1] provides the theoretical and practical tools to study the probability and capability of components to perform their required functions for desired periods of time without failure with desired level of confidence.

The purpose of this research is to determine the performance capability of the electric altimeters that are used in the Boeing 737 aircraft. The primary focus of the study is to determine the reliability of the altimeter from failure data and determine the major cause(s) of failure. The specific objectives of this research are as follows:

1. Gather failure data from aircraft log pages and the repair history database.
2. Apply statistical tools and reliability methodologies to the failure data.
3. Analyze the results, determine the major cause(s) of failure, and predict the reliability of the component.

Assumptions:

1. The data gathered for the analysis are correct and accurately reflect the failure rate of the electric altimeter.
2. All the electric altimeter units under consideration have the same design.
3. The aircraft flies an average of six flight hours per day and 7 days per week.

This work was performed for a local aircraft carrier. This airline is the fifth largest domestic airline employing approximately 36,000 aviation professionals worldwide. This airline operates approximately 3,500 flights per day and serves more than 230 locations in the U.S., Canada, Europe, the Caribbean and Latin America. It has a fleet of 348 mainline jet aircrafts and 300 regional jets and turbo-prop aircrafts offering 17,000 daily flights to 879 destinations in 160 countries worldwide. The aircraft fleet considered for this study is the Boeing 737-300/400 with 68 aircraft.

The Electric Altimeter:

The electric altimeter (the subject of this study) is a part of the instrument panel in the flight deck that provides altitude information. Three electric altimeters can be found in the flight deck of a B737 (as shown in Figure 2). The electric altimeters are electro-mechanical devices. This study will focus only on the captain's and first officer's electric altimeters. A third electric altimeter, called the standby electric altimeter, is not included in the scope of this study. In the case of an electric altimeter discrepancy (inconsistency or variation), the unit in question is removed and replaced with a serviced/operational unit. The removed unit is sent to the Original Equipment Manufacturer (OEM) or a third-party vendor for testing and/or overhaul and/or replacement of parts if necessary. Due to the increase in the number of unscheduled removals in recent years, a reliability review is being conducted on the Boeing 737 electric altimeters.

Figure 2. A view of the instrument panel at the flight deck of a B737

Methodology:

Failure data from operational aircrafts provide a good benchmark of current component reliability. Airlines maintain a database that covers the history of maintenance performed on every aircraft. This provides a good source of historical data regarding airplane component failures and replacements. The failed component under consideration is the electric altimeter.

The methodology employs a fault-tree analysis to study the root cause/causes of failure. First, the failure mode at the aircraft level is determined. The top reasons for removal of the electric altimeter from the aircraft and the top corrective actions taken from the aircraft's perspective are studied. Aircraft log pages describe the discrepancies reported by pilots while the aircraft is airborne. The corrective action refers to the action taken by the maintenance crew to correct the discrepancy before the aircraft's next flight. These data sets are obtained from company databases and transported to an excel spreadsheet to review the top discrepancies and corrective actions. Second, the failure mode at the component level is required for the FTA. The altimeter units that need repair are usually sent to the OEM or a third-party vendor. The shop findings and the shop corrective actions taken by the vendor are available in the form of tear-down reports. Data gathered for a one-year period is used to perform component review. Data gathering consists of the information that answers the following questions.

1. What was the failure mode?
2. What was the shop finding?
3. What was the corrective action?

Results of the analysis are used to create the Fault Tree. FTA provides a formal method of determining the combinations of primary events that result in the occurrence of a specified system or component level event. Fault trees also provide a graphical representation of the component being studied, and their use often results in the discovery of failure combinations that would not have been obvious if other failure identification methods were used. Fault trees are useful for both qualitative and quantitative analysis. A qualitative approach is considered in this study.

Fault-Tree Construction:

Fault trees are built from gates and events. A list of fault-tree gates and events used in the study is described in Figure 3. The Conditional Event can be a Top Event or an Intermediate Event. The Top Event is the foreseeable undesirable event to which all fault-tree logic flows. The Intermediate Event is the system state produced by the preceding events.

The following **constraints** are considered for the FTA:

- Only failure data between July 2007 and June 2008 will be considered.
- Human-induced failures are not included.
- If the unit replaced is a borrowed part from another aircraft, it is not included.
- Only those units that have repair orders generated will be considered.

Fault-Tree Analysis:

The Fault-Tree Diagrams (FTD) (4(A) to 4(G)) are shown in Figures 4(a-g). The elements in the tree are read from left to right. Its Top Event is “Removal of the Electric Altimeter.” (Refer Figure 4(a). FTD A).

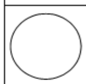
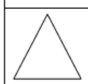
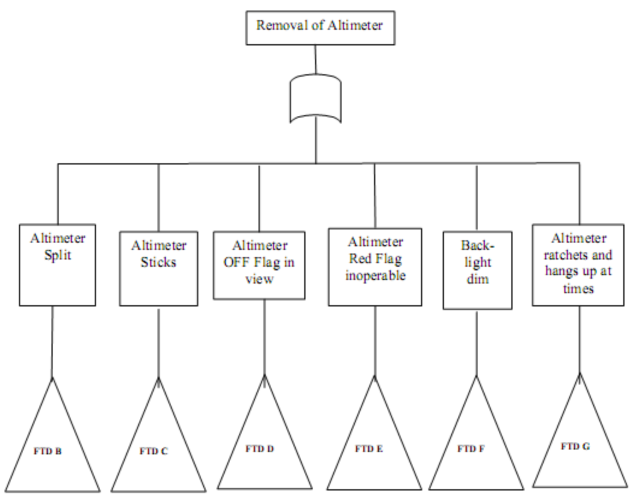
Symbol	Name	Description
	OR Gate	The event above this gate occurs if any of the events below this gate occur.
	Conditional Event	Conditional events are dependent on primary events.
	Primary Event (also known as a Basic Event)	The lowest level of failure possible.
	Triangle	Used to repeat a portion of the tree or to continue the tree on another page.

Figure 3. Fault-tree symbols



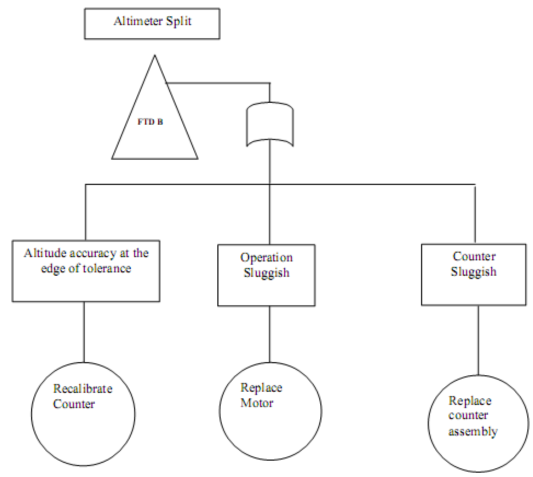
Fault Tree Diagram (A)

Figure 4(a). FTD(A)

At the second level of the fault tree, there are six Intermediate Events (IE) feeding into the top event. The occurrence of any of the IE will cause the removal of the electric altimeter. The events on the second level are:
1. Altimeter split (FTD B) 2. Altimeter sticks (FTD C) 3. OFF flag in view (FTD D) 4. Red flag inoperable (FTD E) 5. Backlight dim or inoperable (FTD F) 6. Altimeter ratchets (FTD G)

1. Altimeter split (refer Figure 4(b): FTD B)**:** This event occurs if any or all of the events at the third level occur.
Altimeter accuracy at the edge of tolerance: This event results in the following Primary Event: Recalibrate counter.
Operation sluggish: This event results in the following Primary Event: Replace motor.
Counter sluggish: This event results in the following Primary Event: Replace counter assembly.

2. Altimeter sticks (Refer Figure 4(c): FTD C): This event occurs if any or all of the events at the third level occur.
Pointer sticks or oscillates: This event results in the following Primary Event: Replace motor.



Fault Tree Diagram (B)

Figure 4(b). FTD(B)

Noisy motor and bearings: This event results in the following Primary Event: Replace motor.
Synchro brushes worn: This event results in the following Primary Event: Replace synchro assembly.
Baro and bug knobs stiff: This event results in the following Primary Event: Replace knobs and set screws.

3. OFF flag in view (Refer Figure 4(d): FTD D): This event occurs if any or all of the events at the third level occur.
Pointer sticks: This event results in all or any of the following Primary Events: Replace pointer, Replace synchro.
Noisy motor: This event results in the following Primary Event: Replace motor.
Flag sticks: This event results in the following Primary Event: Replace flag assembly.
Baro sluggish: This event results in the following Primary Event: Replace knob set screws.

4. Red flag inoperable (Refer Figure 4(e): FTD E)**:** This event occurs if the event at the third level occurs. Pointer sticks intermittently: This event results in any or all of the following Primary Events: Replace motor. Replace pointer and hub assembly.

5. Backlight dim or inoperable (Refer Figure 4: FTD F)**:**
This event occurs if the event at the third level occurs.
Fails light test: This event results in the following Primary Event: Replace dial lamps.

6. Altimeter ratchets: This event occurs if any or all of the events at the third level occur.
Pointer sticks: This event results in the following Primary Event: Replace motor.
Operation sluggish: This event results in the following Primary Event: Replace motor.

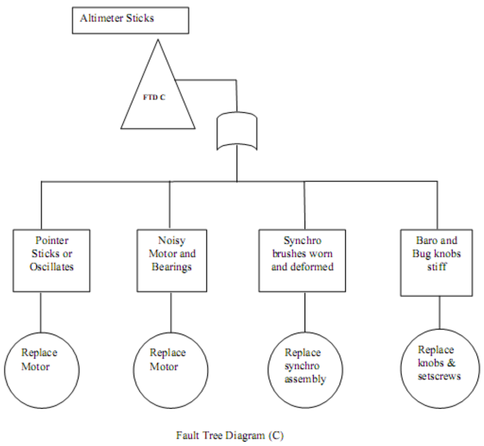


Figure 4(c). FTD(C)

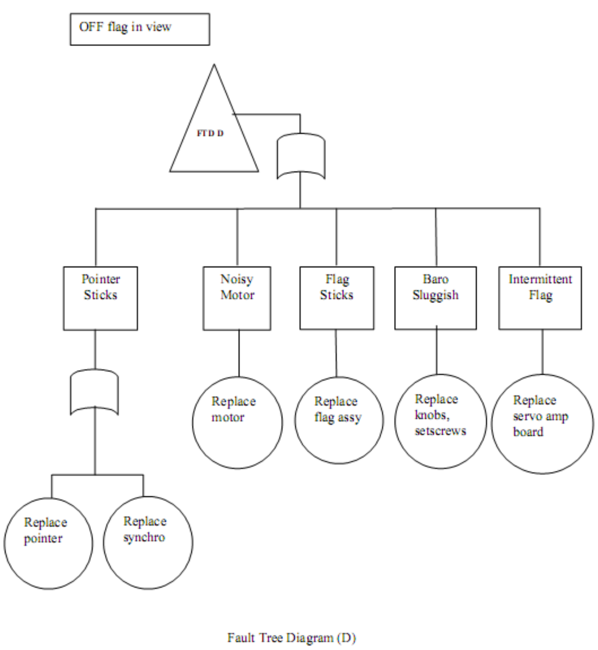


Figure 4(d). FTD(D)

It is seen from the Fault-Tree Analysis that the most common primary event is the replacement of the motor and thus it is reasonable to conclude that most failure modes occur because of failure of the motor. Detailed analysis of the motor hardware (poles, rotors, brushes etc.) is not within the scope of this study.

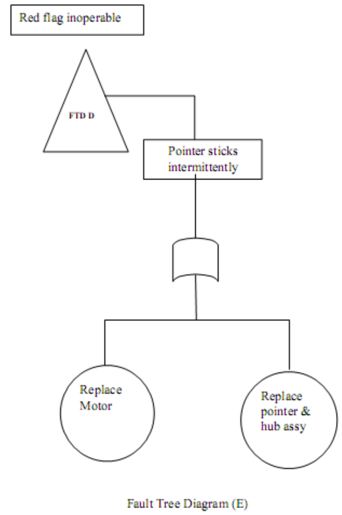


Figure 4(e). FTD(E)

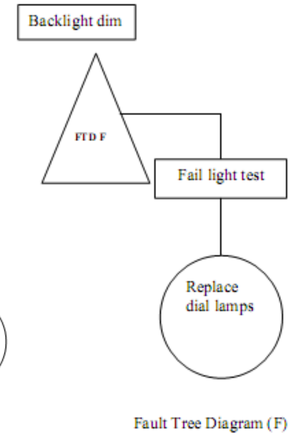


Figure 4(f). FTD(F)

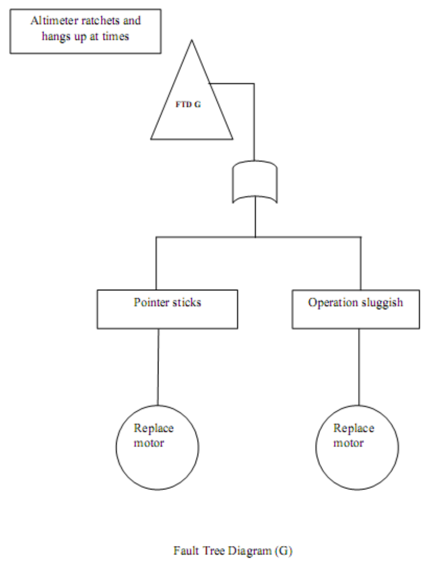


Figure 4(g). FTD(G)

Statistical Methodology

The Mean Time Between Failures (MTBF) is used for units, which are repairable, such that they can be reused after each failure and repair. Such a sequence of times of operation until the next failure is defined as MTBF. The statistical data analysis methodology is widely used for reliability studies [2-3]. The two-parameter Weibull, described in the next section, is one of the most commonly used distributions in reliability engineering. It is a time-dependent distribution that can be used to model increasing, constant, and decreasing failure rates.

The Reliability Function

The Weibull reliability function is given by

$$R(t) = e^{-(\frac{t}{\mu})^{b}} \quad (1)$$

Beta (β) is referred to as the shape parameter. If β is less than one, the failure rate is decreasing over time. If β is greater than one, the failure rate is increasing over time. If β is equal to one, the failure rate is constant over time. Alpha (α) is called the characteristic life. This is the value at which (when t = α) 63.2% of all Weibull failures occur regardless of the shape parameter.

The Goodness of Fit

The method of least squares is used to fit a straight line to a set of points to determine the estimates of the parameters of the two-parameter Weibull distribution. A measure of how well a linear model fits the data is found using the correlation coefficient, denoted by ρ. It is a measure of the correlation between the median ranks and data. Median ranks are the values used to estimate the cumulative distribution function (CDF) for each failure F(t_i) , (e.g., Bernard's approximation MR = (j-0.3)/(N+0.4) where j is the rank failure position and N is the total number of failures observed). The correlation coefficient is calculated using:

$$r = \frac{s_{xy}}{(s_x s_y)} \quad (2)$$

where s_{xy} is the covariance of x and y, s_x is the standard deviation of x, s_y is the standard deviation of y. The range of ρ is $-1 \leq \rho \leq +1$. Values of $\rho \geq 0.75$ are desirable [8]. However, values of $\rho \geq 0.90$ are more desirable. A value of +1 is a perfect fit with a positive slope while -1 is a perfect fit with a negative slope. When the value is closer to ±1, the paired values (x_i, y_i) lie on a straight line.

The Failure Rate Function

The failure rate function, λ(t), provides the relationship between the age of a unit and the failure frequency, or the number of failures occurring per unit of time at age t [4,5]. If the times to failure of identical units follow the Weibull distribution, then the failure rate is:

$$l(t) = \left(\frac{b}{a}\right)\left(\frac{t}{a}\right)^{b-1} \quad (3)$$

Data acquisition for the statistical analysis consists of the following information:

1. What is the unit number of the component that failed?
2. When did it fail?
3. After how many flight hours did it fail?

The hours considered is the Time Since Repair (TSR) expressed in Flight Hours (FHS). TSR is the time accumulated since the unit was last repaired [6]. A spreadsheet prepared with the three parameters for the 1 year period (July 2007 to June 2008) is shown in Table 1.

In order to provide a long-term failure pattern, and for validation purposes, historical data from 1985 to 2008 is also gathered for the analysis. Two subsets of this historical sample, comprised of a 5-year data set and a 10-year data set, are analyzed for the medium- (3 years) to long-term failure (>3 years) rate. The 5-year data set is comprised of failures between 2003 and 2007. The 10-year data set consists of failures between 1999 and 2008.

Table 1: 1 year data (July 2007 to June 2008)

Unit No:	Date Removed	TSR (FHS)	Unit No:	Date Removed	TSR (FHS)
1	7/1/07	35,427.6	20	12/7/07	60,948.1
2	7/23/07	185.3	21	12/19/07	7,358.0
3	7/25/07	14,664.4	22	1/12/08	2,767.3
4	7/29/07	4,101.0	23	1/13/08	15,354
5	7/29/07	2,349.2	24	1/22/08	92.9
6	8/4/07	31,092.4	25	1/31/08	2,358.2
7	8/24/07	5,195.2	26	2/2/08	20,976.9
8	9/8/07	2,379.5	27	2/7/08	27,894.1
9	9/12/07	1,207.9	28	2/11/08	10,310.7
10	9/14/07	41	29	2/14/08	889.5
11	9/22/07	4,620.4	30	2/28/08	3,168
12	10/5/07	58,714	31	3/1/08	657.7
13	10/14/07	1,972.4	32	3/10/08	2,090.6
14	10/28/07	12,036	33	3/15/08	22,880.8
15	11/1/07	6,412	34	3/27/08	34,662.2
16	11/7/07	2,091.9	35	4/6/08	279.9
17	11/18/07	495.9	36	4/17/08	501.3
18	12/2/07	3,238.7	37	4/25/08	6,101.7
19	12/3/07	8,185.2	38	4/27/08	17,663.5
			39	5/4/08	27,513
			40	5/30/08	1,755

Mean Time Between Failure (MTBF)

This airline utilizes a proprietary 'Black Box' SCEPTRE (System Computerized for Economical Performance, Tracking, Recording and Evaluation) to determine the MTBF for the 1-year period. The MTBF computed by the proprietary SCEPTRE algorithm is shown in Table 2. It was felt important to validate the results provided by SCEPTRE via rigorous statistical analysis and compare them to MTBF specifications of OEM. The OEM (General Electric) provided the current fleet-wide MTBF for multiple aircraft carriers as shown in Table 3. The MTBF provided by the OEM is compared to the MTBF calculated using SCEPTRE software and the results are shown in Table 4.

Table 2: MTBF computed by SCEPTRE

Cell Range	Unit Experience	Confirmed failures	Rate per cell	Probability per cell	Cumulative probability
0 - 9998	211844.42	17	0.792	0.547	0.547
9999 - 19997	19225.25	3	1.689	0.815	0.916
19998 - 29996	10559.46	5	3.252	0.961	0.996
29997 - 39995	6087.97	0	0.000	0.000	0.996
39996 - 49994	359.87	0	0.000	0.000	0.996
49995 - 59993	0	0	0.000	0.000	0.996
59994 - 69992	1183.85	0	0.000	0.000	0.996
69993 - 79991	380.91	0	0.000	0.000	0.996
79992 - 89990	0	0	0.000	0.000	0.996
89991 - 99989	0	0	0.000	0.000	0.996
TOTAL	249641.73	25	0.100	Rate per 1000 hours	
MTBF	**9986**				

It can be concluded that the MTBF computed by SCEPTRE is comparable to the MTBF provided by the OEM. Unfortunately, the SCEPTRE system does not provide any detailed insight on type of distribution used, distribution parameter values, and confidence limits. It is neither flexible nor convenient to use. Thus, in order to gain a better understanding, we decided to process 'raw' data from aircraft logbooks and maintenance records to get 'true' MTBF.

Statistical Analysis:

Here we present a rigorous statistical analysis and computation of Weibull distribution parameters. Using Table 1, the times-to-failure data, its rank and the corresponding median ranks for the sample of 40 units are computed (1-year dataset, units failed in the period 2007 to 2008) and presented in Table 5. The probability plot for the 1-year (2007 to 2008) data is presented in Figure 5. From the Weibull probability plot (Figure 5), $\alpha = 9078$ and $\beta = 0.6960$. These parameters can also be mathematically determined using the method of Least Squares [7-9].

Table 3: Current fleet wide MTBF provided by OEM

Operator	Date Period	Flight Hours	Removals	Failures	MTBF
Airline 1	05/07 -10/08	73242	7	4	18311
Airline 2	12/06 -11/07	20472	3	n/a	n/a
Airline 3	01/07 - 2/07	25287	2	2	12644
Airline 4	03/07 -02/08	125868	34	n/a	n/a
Airline 5	01/07 -02/07	283458	45	39	7268
Airline 6	10/ 06 -09/07	95900	6	1	95900
Total (Sample)		477887	60	46	**10389**

Table 4: Comparison of the MTBF

	SCEPTRE	**OEM**
MTBF	9986	10389

Table 5: Rank table for the 1 year data

Flight Hours(T)	Rank	Median Rank (MR)	Flight Hours(T)	Rank	Median Rank (MR)
41.0	1	0.0173267	4,620.4	21	0.512376
92.9	2	0.0420792	5,195.2	22	0.537128
185.3	3	0.0668316	6,101.7	23	0.561881
279.9	4	0.0915841	6,412.0	24	0.586633
495.9	5	0.1163366	7,358.0	25	0.611386
501.3	6	0.1410891	8,185.2	26	0.636138
657.7	7	0.1658415	10,310	27	0.660891
889.5	8	0.1905940	12,036	28	0.685643
1,207.9	9	0.2153465	14,664	29	0.710396
1,755.0	10	0.2400990	15,354	30	0.735148
1,972.4	11	0.2648514	17,663	31	0.759900
2,090.6	12	0.2896039	20,976	32	0.7846534
2,091.9	13	0.3143566	22,880	33	0.8094059
2,349.2	14	0.3391089	27,513	34	0.8341584
2,358.2	15	0.3638613	28,688	35	0.8589108
2,379.5	16	0.3886138	31,092	36	0.8836633
2,767.3	17	0.4133663	34,662	37	0.9084155
3,168.0	18	0.438118	35,427	38	0.9331683
3,238.7	19	0.4628712	58,714	39	0.9579207
4,101.0	20	0.487623762	60,948.14	40	0.982673267

The slope of the best-fit straight line through the data found using linear regression is 0.70, which is the estimated value of β. The y-intercept of the best-fit straight line through the data is -6.23. The estimated shape of the parameter is:

$$\mu = \exp\left\{ -\frac{-6.23}{0.684} \right\} = 9029 \quad (4)$$

To determine the goodness-of-fit, the correlation coefficient ρ needs to be determined.

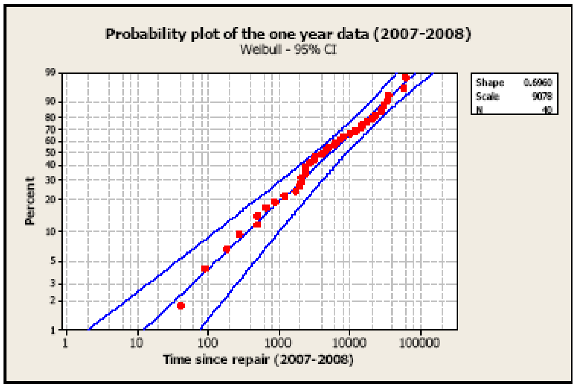


Figure 5: Probability plot of the 1-year data

The correlation coefficient equation is:

$$r = s_{xy} / (s_x s_y) \quad (5)$$

The above equation can be re-written as:

$$r = \frac{\sum x_i y_i - \left(\sum x_i \sum y_i\right)/N}{\sqrt{\left(\sum x_i^2 - \left(\sum x_i\right)^2/N\right)\left(\sum y_i^2 - \left(\sum y_i\right)^2/N\right)}} \quad (6)$$

Where $\sum x_i = 331.73$; $\sum y_i = -22.32$; $\sum x_i y_i = -102.24$; $\sum x_i^2 = 2872.27$; $\sum y_i^2 = 69.69$; $N = 40$

or

$$\rho = 0.9946 \quad (7)$$

Since ρ is close to 1, it can be concluded that the Weibull distribution represents the failure data very well. Substituting the values of β = 0.70 and α = 9029 in the Weibull reliability function given by equation (1), for t = 1000,

$$R(t) = 0.80 \quad (8)$$

Therefore, the probability that the unit will function without failure for 1000 flight hours is 0.80 and the instantaneous failure rate is given by the Hazard function, and is estimated by

$$\lambda(t) = \left(\frac{\beta}{\alpha}\right)\left(\frac{t}{\alpha}\right)^{\beta - 1} \quad (9)$$

For t = 1000, the hazard rate is

$$\lambda(t) = 1.52\text{E-}04 \quad (10)$$

A similar analysis to compute Weibull parameters was carried out on the 5-year dataset. Weibull plot obtained for the 5-year dataset (2003 to 2007) is shown in figure 6. It is noted that 116 electric altimeters are considered for this analysis (i.e. the number of samples N = 116).

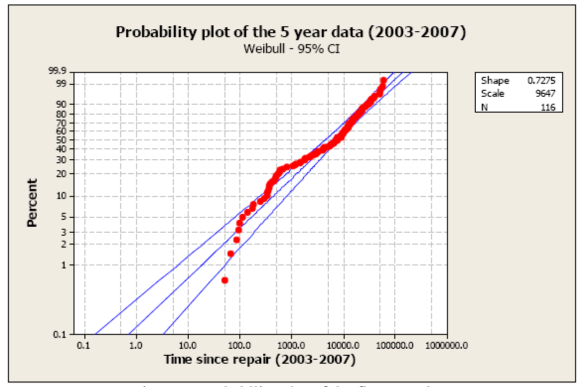


Figure 6: Probability plot of the 5-year data

Substituting the values of β = 0.7275 and α = 9647 in the Weibull reliability function,

For t = 1000, $R(t) = 0.825$ (11)

Therefore, based on 5-year dataset, the probability that the unit will function without failure for 1000 flight hours is 0.825. The instantaneous failure rate given by the Hazard function (based on the 5-year dataset) is estimated as

For t = 1000, $\lambda(t) = 1.40\text{E-}04$ (12)

A similar analysis was carried out for the 10-year dataset (1999 to 2008) with 248 altimeters. The details (omitted here for brevity) of this 10-year dataset analysis can be found in the recent work by Samuel [10]. The probability that the unit will function without failure for 1000 flight hours (based on 10- year dataset) is 0.85 and the instantaneous failure rate given by the Hazard function (based on the 10-year dataset), estimated for t = 1000, is 1.33E-04.

Summary of Results

The Fault-Tree analysis revealed that the failure of the motor to be primary cause of the most electric altimeter failures. The calculated MTBF of 9986 FHS was comparable to the current fleet-wide rate of 10389 FHS. The reliability values were calculated with three sets of data, i.e., for the 1-year period (2007 to 2008), 5-year period (2003 to 2007) and 10-year period (1999 to 2008). Table 6 compares the estimated reliability probability for 1000 FHS.

Conclusion

This study focused on utilizing historical failure data to determine the reliability of the electric altimeter used on Boeing 737 aircraft. The failure mode reflected real-world operational conditions that each unit experienced in flight.

Aircraft logbooks provided the actual discrepancies while tear-down reports provided the shop findings and corrective actions. An FTA was used to determine the major cause of component failure. Statistical analysis was applied to the failure data to estimate the failure rate and the reliability of the electric altimeter. A review of the literature provided insight into the use of the Weibull distribution as a commonly used methodology to calculate the reliability of a system or component. The goodness-of-fit test proved that the Weibull distribution fit the failure data well.

Table 6: Comparison of the reliability estimates

Data collected for:	No. of Altimeters	Estimated Reliability at t = 1000 FHS	Estimated Failure Rate at t = 1000 FHS
1 year (07-08)	40	0.80	1.52E-04
5 years (03-07)	116	0.825	1.40E-04
10 years (99-08)	248	0.85	1.33E-04

In this work, three sets of failure data were analyzed. A more recent time period from July 2007 to June 2008 provided the 1-year failure data set. Historical failure data collected from 1999 to 2008 provided the 10-year data set and 2003 to 2007 periods provided the 5-year data set. The fault tree analysis performed on the 1-year data revealed that the altimeter motor was the major cause of failure. The MTBF was estimated to be 9986 FHS that matched the MTBF provided by the OEM. Statistical methodologies were applied to all data sets and the results were compared. For 1000 flight hours, the reliability is estimated to be 0.80, which means that there is an 80% chance that the unit will function successfully for the first 1000 flight hours. For the aircraft electronics technology community, this study provides benchmark data for altimeter reliability. These reliability estimates can also be used to determine the reliability at the system and aircraft level, and can be utilized to perform a System Safety Analysis (SSA).

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