An Estimation of the Optimal Time of Maintenance Interval in the Aircraft Systems Using Fault Tree Analysis

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Abstract

Aircrafts maintenance is a major and complex activity with aiming to achieve high standards of safety and attain an increased level of reliability of system at the lowest possible cost. therefore, estimation of failures risk of aircrafts has become necessary. The paper aimed for estimating failures risk in order to determine an optimal time for starting in the maintenance activities using Fault Tree Analysis (FTA) approach. The FTA approach uses scenarios to identify a critical equipment that can effect on the operating performance the aircrafts. Based on the estimated risk scenarios that extracted through maintenance records of aircrafts, the results showed that FTA approach has able to estimate the failures risk for any critical equipment run under different environmental conditions.

Keywords: Maintenance, Risk assessment, Critical equipment of aircraft, FTA.

1. Introduction

Maintenance is the combination of technical and administrative tasks conducted to return component to the normal operation conditions in order to perform its function. Maintenance event has become necessary for every component if it was designed well, hence, application of maintenance is regarded as a necessary event over the years, especially the aircrafts maintenance which have clear and wide targets to increase safety factor to mitigate the risk levels. In addition, an increase of life span of component, reduce degradation prior to occurrence of failures.

Aircrafts consist of complex equipment pieces that operate simultaneously, and in-between each there are components and items. Any defect in these components may lead to many failures. Therefore, aircrafts are always faced many accidents, serious financial and human consequences due to catastrophic failures. The applications of an appropriate maintenance contribute greatly in the reduction of these consequences at the lowest possible cost. These applications involve corrective and preventive maintenance [1]. An implementation of scheduled maintenance includes the replacement, repair activities to prolong life of equipment capability, and avoid the premature deterioration of a system [2].

It is normal that aircrafts will have to be in service as much as possible [3], this needs to increase awareness of the maintenance fact to ensure a very low level of risk and high level of reliability. The development of a maintenance strategy may be faced many challenges, but can be enhanced by using the effective approaches and tools such as Risk-Based Failure (RBF).

Many accidents of aircrafts have been happened due to poor maintenance scheduling that resulted in postponing lubrication activities of aircraft. This simple problem led to a loss of aircraft longitudinal control and then finally a crash [4]. Maintenance event must be considered as an important part for any air operating that serves aviation sector. Therefore, many manufacturers and airline companies should be realized that there is a critical need to develop effective tools in order to schedule maintenance program [5]. These tools will contribute in improving the time performance of the scheduled travel as a vital factor to satisfy current customers and create new customers [6]. The purpose of this paper is to present FTA approach, for estimating failures risk in order to determine an optimal time for starting in the maintenance event based on critical failures / components related to the aircrafts.

2. Determination of Maintenance Interval

The used approach to determine maintenance activities of aircraft systems mainly depends on Maintenance Steering Group (MSG). The MSG relies on the consulters and engineering experience [7] to determine maintenance interval. The performance of all the maintenance activities of aircraft systems were not optimal intervals in terms of practical, which may ultimately effect on the aircraft performance and the economics aspects of company.

The recommended maintenance activities by OAMs of some equipment pieces of aircraft perform during the predefined intervals in the form of checks based on the codes and number the Flight Hours (A: every 500FH, B: every 1000FH, or C: every 5000FH). However, this maintenance strategy cannot be performed on the long term, because operating conditions vary significantly from an aircraft to another. Therefore, components maintenance of any aircraft must be performed during a certain time at every few weeks/months/years according to the operating conditions and the residual life of the critical pieces of equipment.

3. Risk-Based Failure (RBF)

RBF analysis in this study identifies the critical components in the aircrafts, which occur repeatedly and impact the operational conditions of aircraft. These failures may have high risk on the aircraft performance. Therefore, elimination or reduction of failures cannot be unless maintenance scheduling is accurately estimated based on the critical components. In order to avoid these events, it is necessary that the focus should be on the undesirable failures. These failures usually occur due to the operating conditions, human errors and poor maintenance activities. The failures causes can be described as shown in Figure 1 [8]:

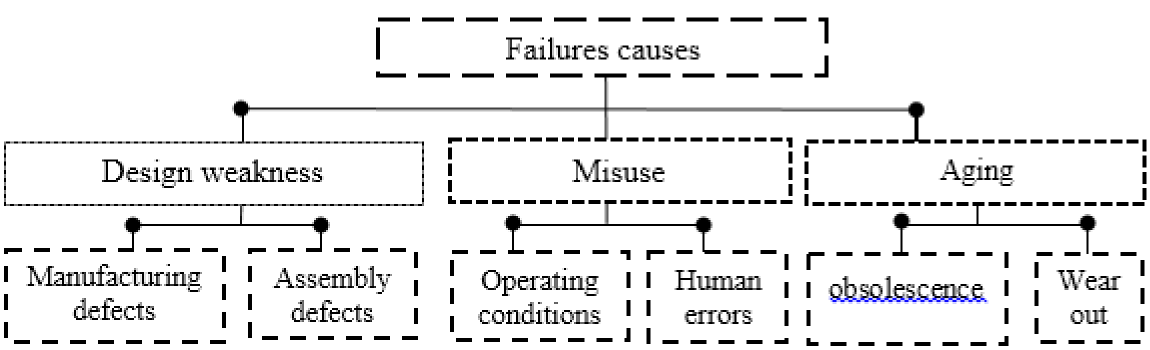

Fig.1 Classification of failures cause

Design failure occurs due to an inadequate specification and improper implementation. Most common failures in rotating equipment. Design weakness occurs due to inherent or induced weakness in the system resulting from excessive stresses. Misuse occurs due to misuse of the system resulting from human error or operating conditions. Aging occurs due to the expected failures resulting from obsolescence or wear-out due to the poor maintenance [9].

3.1. Fault Tree Analysis (FTA)

FTA is a tool that aims to provide an effective mechanism, evaluate and control risks, determine root causes, and identify critical component and paths. FTA uses to solve a wide variety of problems associated with safety and management issues. Also, this tool takes probability and reliability theory into account to prevent risks and failures by means of qualitative and quantitative methods to identify the area that can be unsafe in a system operation. Thus, FTA has become a well tool for many corporations that run under harsh operation conditions to apply on steady basis of safety and reliability. The fault tree can provide a diagrammatic description of the way in which a system can fail in a specific mode. It can be executed quickly to provide unique insights about how the system fail, and what can be done to avoid or reduce the risk associated with a system [10].

The essential concept of FTA translates the failure behavior of complex system into a structured logic diagram (called a fault tree) to identify specific causes which can lead to undesired event (called the top event), and a logic model which provides a mechanism to assess risk either qualitatively or quantitatively to provide useful information on the causes of the undesired top event or significant information on the probability of the top event respectively. Thereby, FTA depends on Boolean algebra, probability and reliability theory to define undesired events and describe fault paths of events [11]. FTA can be divided into four main stages:

1. Identification of Top and Sup – Event (TE &SE),
2. Development of Failure Logic (FL).
3. Determination of Minimum Cut Sets (MCS's) using MOCUS Algorithm.
4. Determination Cut Sets importance.

These stages aim to convert complex process to the logical diagram to construct failures tree for each event in order to identify critical failures and describe path for each component that can be derived from Minimum Cut Set (MCS). These failures are categorized into two types of possible events, namely indirect and direct failures. Whereas the indirect failures are described as failures that are not be impacted on the functional performance of aircraft. The direct failures are associated with failures which may be caused the critical events, which can be classified into internal and external failures.

Figure 2 shows the main components of simple aircraft in which requires high reliability to avoid frequent failures and stoppages that may be hampering the operating process due to human error or operating conditions. The main components of aircraft can be classified as following:

1. Power Transfer Unit (PTU)
2. Ram Air Turbine (RAT)
3. Hydraulic Motor-Driven Generator (HMDG)
4. Engine Driven Pump (EDP)
5. Stabilizer Trim Motor (STM)

6 AC Motor Pump (ACMP)
7 Leading Edge Slat Drive Motor (LESDM)
8 Emergency Passenger Door Actuator (EPDA)
9 Trailing Edge Flap Drive Motor (TEFDM)
10 Nose Wheel Steering System (NWSS).

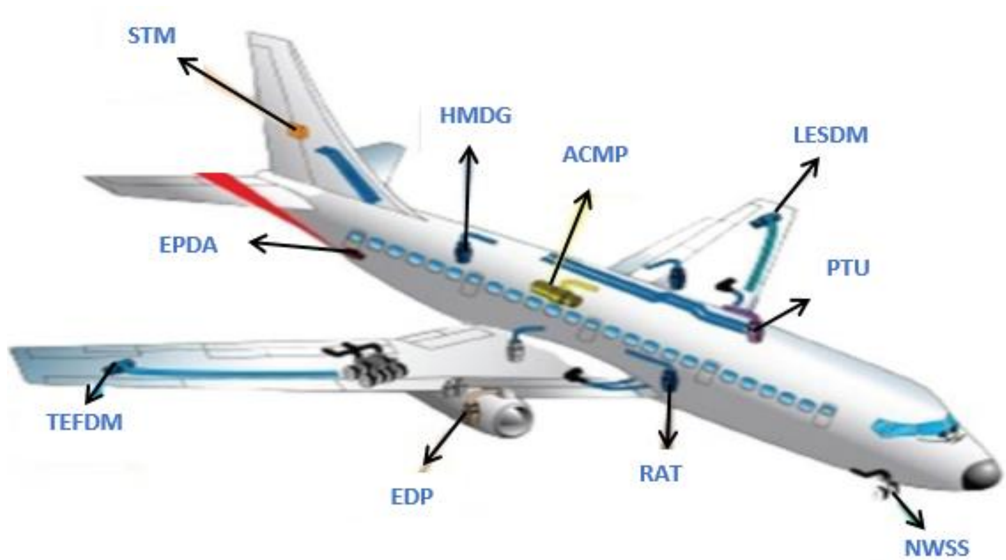

Fig. 2 Schematic diagram of simple aircraft

4. Engine Driven Pump as a Case Study

The EDP is one of critical equipment pieces that effects on both the operating and technical capability of the aircrafts. These failures can cause various risks during the landing and flight distances, take-off weight, and high drag coefficients. These failures cause also operational interruptions which affect seriously on the rate and quality of flight. Therefore, theses failures can express by the risk consequences that occur due to the inability of equipment to perform its functions in a timely fashion. The failures that have operational consequences should be taken into account whether the aircraft is on the ground or in the air. The effect of failures in the air can lead to a back to the gate, a diversion, a go-around, or re-routing. The effect of failure on the ground can lead to a delay in the flights at departure, at arrival, an aircraft substitution, or a flight cancellation.

An unplanned maintenance may also be potentially harmful to the scheduled operation of the aircrafts, and may lead to delays or cancellations consequences and increase in the operational and maintenance costs and irregularities, which the flight crew may also have to refer to the crew check emergencies lists. In the event of such a type of maintenance occurring to different degrees, many contributory factors should be taken into account to recognize the defects and deviations that impact on the rate and quality of flight production in order to identify an approach to estimate optimal time to implement maintenance event.

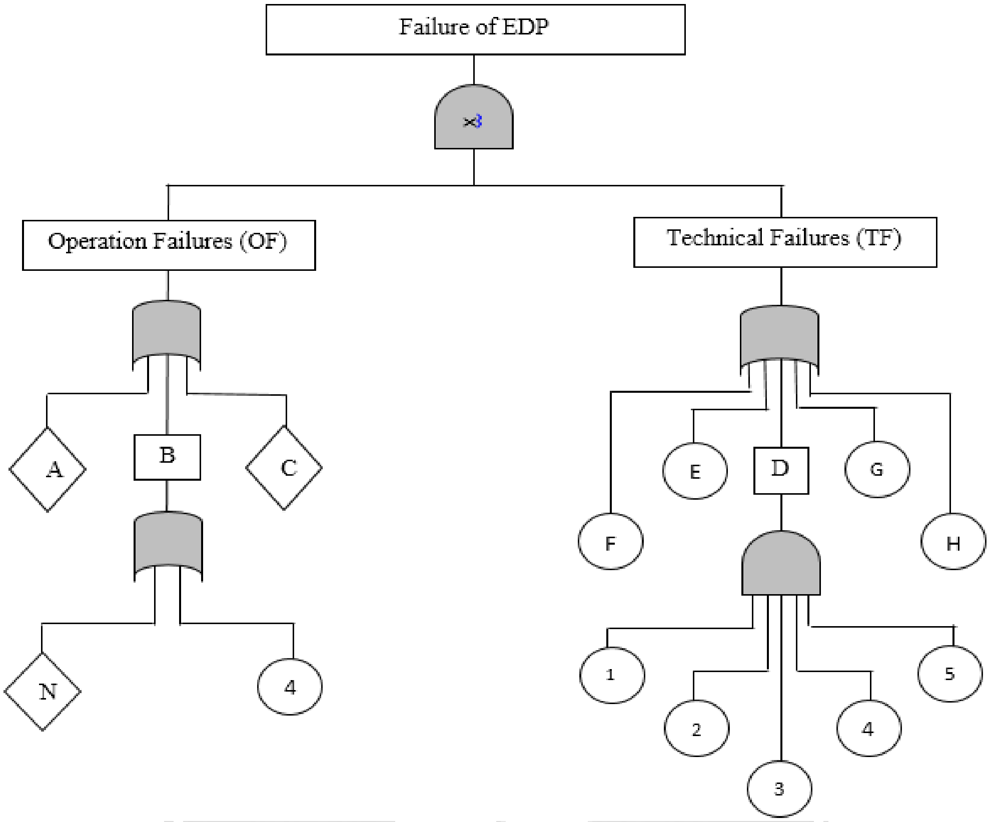

Fig 3. FTA of critical failure in EDP of aircraft

A: Applying abnormal procedures
B: Deferring
C: Imposing restrictions
D: Failure prior to take-off
E: Failure during Take-off
F: Failure during Climb
H: Failure landing

G. Failure during Cruise
N: No impact on operating
1. Airborne delay
2. Ground delay at departure
3. Ground delay on arrival
4. In-flight turn-back
5. Diversion

Probability of failure for EDP = OF x TF
TF = F + E + D + G + H
D = (1.2.3.4.5)
OF = A + B + C
B = N + 4
CS = (F + E + G + H) + D + A + B + C
CS = F + E + G + H + (1.2.3.4.5) + A + B + C
CS = (F + E + G + H + 1.2.3.4.5). (A + N + 4 + C)
Assume that 1.2.3.4.5 = V

$$CS = \begin{cases} \text{Scenario I: } (\mathbf{F.A}) + (F.N) + (F.4) + (F.C) = 0.0729 \\ \text{Scenario II: } (E.A) + (\mathbf{E.N}) + (E.4) + (E.C) = 0.2847 \\ \text{Scenario III: } (G.A) + (G.N) + (\mathbf{G.4}) + (G.C) = 0.2147 \\ \text{Scenario IV: } (H.A) + (H.N) + (H.4) + (\mathbf{H.C}) = 0.2847 \\ \text{Scenario V: } (\mathbf{V.A}) + (V.N) + (V.4) + (V.C) = 0.000239 \end{cases}$$

5. Risk Assessment

Risk assessment is very crucial step in decision making to determine likelihood and consequences of failure. Risk assessment aims to estimate probability of failure and their consequences, which can be qualitative or quantitative [12]. The quantitative approach establishes all details associated with the equipment and other pertinent information based on Maintenance Review Board Reports (MRBR). Risk is then calculated as the product for each probability and consequence of failure scenario, the risk of system being the total of all the scenario risks.

The Tolerable Risk (TR) is the sum of all the risks associated with the possible consequence scenarios in all the operational and technical failures that have resulted from the proposed FTA. Therefore, TR associated with the financial risk can be calculated as:

Tolerable Risk = Probability of Failure x Consequences of Failure

$$TR = PoF_i \cdot \sum CoF_i \qquad i : \# \text{ of scenario} \qquad (1)$$

6. Results and Discussion

Table 1 shows five scenarios, which were determined the ultimate operational consequences based on the possible combination of events and the financial consequences for each scenario using FTA. Seventeen events were identified in which ultimately led to an estimate of TR.

$$TR = (PoFi)|(PoFii).....(PoFv) \times \begin{pmatrix} CoFi \\ CoFii \\ \vdots \\ CoFv \end{pmatrix} \qquad (2)$$

Table 1 Scenarios resulting from EDP failures

Scenario (i)	PoF_i	CoF_i \$/hr		TR (\$/hr)	∑ TR
		Event duration (hr)	Cost (\$)		
I	0.0729	2	17045	1242.6	\$12514
II	0.2847	2	15600	4441.3	
III	0.2147	2	19850	4261.8	
IV	0.2847	2	9000	2562.3	
V	0.000239	2	23100	5.5	
			∑ CoF = \$84595		

The Estimated Risk (ER) is the operational risk of for any equipment, which increase with an operation time of equipment. Vaurio [13] states that ER associated with any process is usually expressed as the following mathematical equation:

$$ER = f(t)_{aircraft.} \sum CoF \qquad (3)$$

Table 2 Probability of failure for EDP components

Component A/B/C			Component D/E/F/G/H			Component V		
Comp.	**# of failures**	**P(t) (hr)**	**Comp.**	**# of failures**	**P(t) (hr)**	**Comp.**	**# of failures**	**P(t) (hr)**
A	3	0.429	D	2	0.142	1	3	0.3
B	3	0.429	E	4	0.285	2	2	0.2
C	1	0.142	F	1	0.073	3	2	0.2
			G	3	0.215	4	2	0.2
			H	4	0.285	5	1	0.1

MCS = (F.A) + (E.N) + (G.4) + (H.C) (V.A) (4)

Probability of Failure for EDP $f(t) = 0.1396$

Reliability of EDP $R(t) = 1 - f(t) = 0.8604$, failure rate (λ) = 3.132E-5 per hr.

$$MTTF = \int_0^\infty \frac{dR(t)}{dt} dt = \int_0^\infty e^{-\lambda t} \quad \text{at} \quad 0 < t < \infty \quad (5)$$

$$MTTF = = \frac{1}{failure\ rate} = \frac{1}{2.08E-4} = 4800 \text{ hrs}$$

The probability of failure and failure rate of EDP can be modelled using exponential distribution: Exponential distribution of EDP components is a reasonable assumption to determine reliability of aircraft.

$$R(t)_{EDP} = Exp\,(-3.132E\text{-}5t) \quad (6)$$

Table 3 Reliability and unreliability of EDP

time (hr)	**3000**	**3250**	**3500**	**3750**	**4000**	**4250**	**4500**	**4750**	**4800**	**5250**
R(t)	0.910	0.903	0.896	0.889	0.882	0.875	0.868	0.861	**0.860**	0.848
***f*(t)**	0.089	0.096	0.103	0.110	0.117	0.124	0.131	0.138	**0.139**	0.151
ER	7586	8187	8783	9374	9961	10543	11121	11694	**11808**	12826

In general, acceptable risk varies from an aircraft to another due to operating conditions and economic aspects. In order to accept risk resulting from EDP failures, it should be ER is equal or lower than TR according to the following constrain.

Estimated Risk (ER) ≤ Tolerable Risk (TR)

The level of acceptance should not exceed $12514 in order to ensure risk mitigation before its occurrence by executing maintenance activities for EDP.

(ER = $11808) < (TR = $12514)

A decrease in the reliability with time results in an increase of the probability of failure of EDP components. This means that estimated risk of EDP would increase to reach up to $11808 at 4800 operational hours. As strategy of Preventive Maintenance (PM) is based on replacement policy. This means that Engine Driven Pump (EDP) should undergo the maintenance activities in order to replace some components of EDP every 4800 hrs. The scheduled maintenance of EDP components every 4800hrs would help in avoiding any threats may lead to increasing in the operational risks due to an increase of the PoF.

7. Conclusions

The results of study are showed that aircrafts have the high of the reliability of system that run redundantly. However, the failures would have a direct adverse impact on the safety and operational function of aircraft. Therefore, according to the recommendations of Original Aircraft Manufacturers (OAMs), aircrafts must be run under the normal operating conditions based on the scheduled maintenance activities to avoid any threat may be occurred such as a delay, cancellation, return to gate or diversion to another airport.

The standards associated with maintenance program have become playing a vital role in development of aviation field in order to implement maintenance requirements on a high level of safety. An inspection is one of requirements that contributes in determining the consequences of failures before its occurrence and selecting an effective decision of maintenance. The paper is designed to present an approach would determine an optimal time for starting in the maintenance activities based on the different operational and technical failures of aircraft system failure.

This paper demonstrated the capability of FTA approach in enhancing reliability and maintenance performance of aircraft systems. The quality and adequacy of the required data of the failure rate and the risk assessment of each event were enough to estimate the optimal time of maintenance every 4800hrs. The FTA can play an important role in achieving accurate results for other components of the aircraft systems. Hence, there is a need to enhance the capability of taking effective decisions to identify optimal interval of maintenance according to the available failures records and their costs.

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