FAILURE MODE IDENTIFICATION AND DATA PREPARATION FOR AEROENGINE RELIABILITY STUDIES

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ABSTRACT
Failure prediction and evaluation of operational reliability of aeroengines is an important activity for the fleet management. Studies have been reported in the literature on the reliability analysis of components and systems but publications on data preparation, validation etc. which is a prerequisite for successful reliability evaluation is scarce. Failure mode identification and data preparation assumes greater significance due to the fact that the utility of the outcome of statistical analysis for operational decisions is limited by the quality of the data that had gone into the analysis. This paper presents the study carried out on failure mode identification and data preparation for reliability analysis of a typical aeroengine operated by the Armed Forces.

Operational success of an engine depends on the collective functioning of several components and for evaluating the system reliability, we need to construct a reliability block diagram, by segmenting the physical structure of the engine into modules/sub-systems without loss of vital information on the system. Procedures adopted for segmentation of a complex physical system into a hierarchical structure, consisting of different modules (subsystems /assemblies), which can further be divided into elementary components have been discussed in the paper. It also illustrates the data extraction on inter arrival times, which are either exact or censored, based on the competing risks set-up

KEY WORDS: *Failure mode identification, Data preparation, Reliability, Life Extension, Field evaluation.*

1.0 INTRODUCTION
In the aviation scenario, the reliability assessment has got considerable attention with the advent of Concorde programme in 1960s. Subsequently, safety and reliability targets formally appeared in military aviation via PANAVIA's requirements for the RB199 engine in Tornado. Due to stringent operational requirements and shrinking budgetary allocations, the Armed Forces became more serious about reliability requirements [9] and in 1990s for the EJ200 engine in `Euro Fighter' Aircraft, numerical safety and reliability target levels had became contractually binding. In such cases, engine manufacturers carry out reliability analysis for demonstrating the safety and reliability target levels during the design stage based on the anticipated failures of the conceptualized design[2]. This analysis heavily depends on the standard failure data bases or the limited in- house test data available which impose an inherent limitation in terms of its inability to account for the deviations from the idealized conceptual design scenario. Hence the reliability predictions made during design stage serve as mere guide lines of the product performance during field operation. In safety critical applications such as aeroengines, the end user (Armed Forces) often needs to verify the claim made by the manufacturer via an alternate route wherein the observed failure rate and failure modes are used as the basis to evaluate the operational reliability.

As the research in the field of reliability has intensified, many procedures and techniques for system reliability assessment have been reported in the literature and a novice reliability practitioner may find it difficult to select the appropriate technique for a particular application. Ascher and Feingold [5] discussed various issues regarding the use/misuse of statistical techniques in reliability analysis of repairable systems and Thompson [16] and many others [5,10,11,12,19] have attempted to clarify the basic issues in modeling the repairable system reliability. A quick scan through the available literature indicates that studies on the failure mode identification of physical systems and data preparation for reliability evaluation are comparatively less. Roger Cooke et. al., [13] has reviewed the concepts and methods on reliability data base design and pointed out the need to address the equipment reliability from a competing risk setup. Since the system reliability is affected by the configuration in which the components are arranged and the practical utility of the outcome of the statistical analysis is influenced by the quality of data that had gone into the model, we need to address data preparation issues as a prerequisite for reliability evaluation. Thus we identify (1) failure mode identification and data preparation for reliability studies and (2) statistical analysis of the data and interpretation as two important aspects of reliability evaluation. In view of the above, we adopt a two tier approach for the analysis of in-service reliability of aeroengines. The first part deals with the structural aspects of the physical system with emphasis on failure modes leading to the development of a Reliability Block Diagram (RBD). It also focuses on data collection in the required format. The second part is about the statistical model used to describe the evolution of the system reliability over the mission time of the engine. In this paper we address the first part, ie., the failure mode identification and data preparation as a prerequisite for modeling the system reliability. The details of the second part, ie, failure rate modeling and assessment of system reliability is provided in [6] and the interested reader is referred to [6] for further details of the statistical modeling.

This paper is organized in the following manner. The hardware configuration as well as the domain of interest for this study are described in section 2. In section 3, we discuss the modularity concepts in aeroengine design. Generalized procedures for segmentation of complex systems have been reviewed and a scheme based on the observed failures has been suggested in section 4. Section 5 is concerned with consolidation of active failure modes based on system knowledge assisted by the actual field experience. Section 6 deals with identification of basic reliability structure of the engine and in section 7 we discuss the extraction of data for reliability evaluation under a competing risk setup.

2.0 THE PHYSICAL SYSTEM

2.1 Hardware Configuration: The failure mode identification and data extraction is demonstrated on a typical turbo-shaft engine which has been chosen to demonstrate the procedure for a typical mechanical system. The physical system considered in the current research work is a single spool turbo-shaft gas turbine engine that delivers 400KW power with the specific fuel consumption of 200 kg/hr.

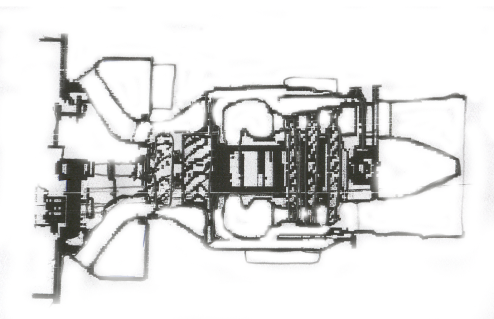

Figure 1 Physical Structure of a Typical Turbo shaft Engine

Figure 1 shows the schematic of the engine, which is a representative of a typical mechanical system. Important constructional features of this engine include a single spool rotor with single stage axial compressor, single stage centrifugal compressor and three stages of turbines. The rotor assembly is supported on bearings which are fixed on the engine casings. The combustion chamber is annular type and the reduction gear mounted on the aft side. Engine functions are controlled by a set of accessories mounted on the engine casings.

2.2 Domain of Interest : The failure definition in a system study varies with the level of analysis and the domain on which the attention is focused. For example, those who study the `physics of failure' are interested in the physical phenomena and the material degradation involved whereas a maintenance engineer, is interested in knowing which component is getting replaced frequently. In this study, we define failure as the incidents where the engine fails to operate satisfactorily, leading to the removal of the engine from the aircraft. Various levels in the hierarchy of analysis is illustrated in figure 2. As given in figure 2, at the level 1 of hierarchy, the scenario of action is a field hangar where the defective engine is replaced with a serviceable one enabling the aircraft to perform the mission. Here the entire engine is acting as a single component replaced at a socket in the aircraft and this defective engine is sent to the maintenance depot for repair.

	Level 1
Scenario	Field Hangar
Failed item	Engine
Action	Replace failed Engine

	Level 2
Scenario	Repair Depot
Failed item	Component Sl.No. (XX)
Action	Replace the Component

	Level 3
Scenario	Design House
Failed item	Design adequacy
Action	Redefine the design

Figure 2. Different Levels of Activities

At level 2 (ie., maintenance depot), the component responsible for failure is identified and replaced in the respective socket of the engine and the engine is made serviceable. At level 3, the failed component is sent for detailed analysis on the `physics of failure' to the design centre for incorporating any possible improvement in the component design so as to prevent the occurrence of similar failures in future. In this paper our attention is focused to level 2 and the system is viewed from a maintenance engineer's perspective. A maintenance engineer at level 2 of the system hierarchy is mostly concerned with replacement (as shown in figure 3) of the failed component and making the engine serviceable in the shortest time possible in an effective manner.

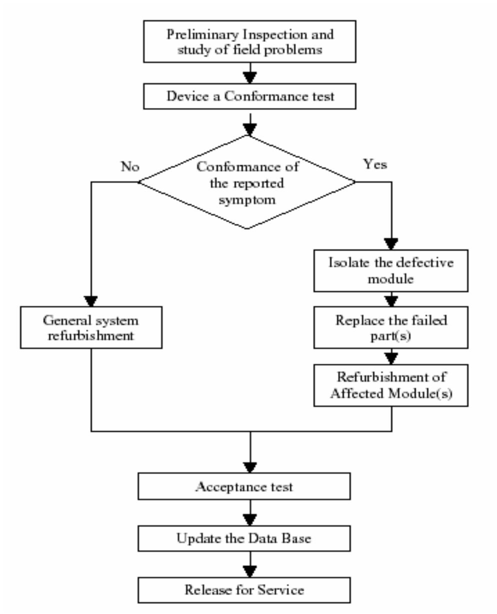

Figure 3. Activities at Level 2

3. 0 MODULARITY IN AEROENGINES

The architecture of a product is the scheme by which the functions of a product are allocated to physical components and the two properties (a) the mapping from functional requirements to physical objects of the system and (b) the degree of decoupling of the functions among the components make the distinction between modular and integral architecture[3]. In modular structure, components implement one to one functions and the components' interactions are well specified. In an integral architecture, there is a complex mapping between the functional elements and components and the components' interactions are ill-defined and coupled giving rise to a challenging task for system decomposition. The modular concept in design of aeroengines was launched by Rolls-Royce by conceiving RB211 in terms of seven basic modules. By the introduction of modularity, Rolls-Royce made an attempt to simplify a highly complex task. Later on the other companies involved in aeroengine industry such as Pratt & Whitney came up with PW4000 family and General Electric Aircraft Engines and SNECMA partnership came up with CFM family of engines. These efforts by major design houses have given an impression that in general, an aeroengine is designed according to modular concept and that system decomposition is a simple task. However, a closer look at the military aeroengines of relatively older generation and currently operated by the Armed Forces reveals that the majority of the ageing fleet of engines are non-modular in their design and decomposition of such a complex system is a challenging task. The level of break-up required essentially depends on the requirement of the study. Since the current study is focused on the in-service reliability evaluation at a system level, the break-up has been presented up to the sub-system/component level.

4. 0 FAILURE SPACE EXPLORATION

As discussed in section 3, for segmentation of engines which are not designed strictly as per the modular concept, we need to evolve a strategy based on the contemporary methods available. In this section, various procedures for identifying and analyzing the failures have been reviewed and a method for segmenting an aeroengine predominantly of integral architecture into different modules for the reliability estimation has been discussed.

The failure identification procedures such as Failure Mode Effect and Analysis (FMEA), Fault Tree Analysis (FTA) etc. are being used for the detection of failure modes. For safety critical systems like aero engine, carrying out Failure Mode Effect and Analysis(FMEA) is a part of the design compliance with the airworthiness regulations. Majority of the literature on failure mode identification deals with the system analysis during design phase. Design FMEA, a bottom-up technique, is one of the methods during the conceptual design phase for providing a mapping between failures and their impact on system functions [4]. FMEA lists out the component failure modes and infers their effect on the system failure modes.

But for operational reliability assessment program, it is prudent to revisit the failure modes of design FMEA in the light of the operational experience gained. In this study we adopt a system for failure mode identification based on the observed failure and subsequent repair carried out. This approach provides a basis for identifying the topology of the system. Our approach differs from the conventional FMEA with respect to the failure criteria selected ie., when FMEA gives prominence to the function which could be disabled in a typical failure, we focus on component failed and replaced consequent to a failure. Further this method depends on the field experience and failure data available rather than the theoretical anticipated failure modes of FMEA. The approach of identifying failure modes based on occurrence data allows examination of a complex mechanical equipment from the component perspective, similar to the case of design models. The FTA structure in this method, supports the system breakdown with regard to hierarchy of failure with engine failure as the top event. If sufficient operational data is available, this approach does not impose any significant limitation on operational reliability assessment. In the light of the following case studies reported in literature, we can see that failure mode identification based on the occurrence data is preferable than a purely theoretical approach for in-service reliability estimation.

A study conducted on consumer products by Srikesh et. al., [14] has reported that of the 1001 components in the component-failure matrix of the FMEA , 867 was from the group of failures frequently occurring during the operation. Of the other 134 components, 8 of them exhibited 2 of the 19 infrequent failure modes and the rest just one of the 19 failure modes. It implies that the failure mode identification based on the observed failure data covers majority of the theoretical failures predicted in the design FMEA. However, design FMEA for complex systems may be a tedious task in which the designer may not be able to conceptualize all the failure modes likely to occur during the post product release regime, as indicated in the study by Allen Atamer [1].

Allen Atamer [1], carried out a study to compare the FMEA and Field Experience of TFE 731 aero engine. He reported that out of 727 failure modes encountered during the field operation only 20% matched with the FMEA anticipated failure modes. The study carried out at the field maintenance level brings out the mismatch between the failure modes of FMEA and the failures observed in the field. Allen Atamer points out that the design FMEA has described the failure modes with lot of technical details which a field service representative seldom uses and contained several failure modes that are extremely unlikely in the competing risk setup. The difference in two methods arises mainly because of the difference in the viewpoints of a designer who concentrates on system function to that of a maintenance engineer who gives priority to real life observable events happening just in front of him. Though the theoretical conceptualization of the failure space using FMEA was satisfactory for simple consumer products, its inadequacy to represent the field scenario of a complex aero engine points to the need for improving the FMEA development process, as mentioned in [8,15,17], which is beyond the scope for our discussion. Nevertheless these examples indicate that for analysing operational reliability of an aeroengine with sufficient operational experience, a failure mode identification technique based on the observed field failure data is more appropriate than depending on theoretically anticipated failure modes extracted from design FMEA.

As seen from the study of Allen Atamer [1], conventional analysis builds upon the basic assumption that design, manufacture, operation and maintenance of the engine strictly conforms to the approved procedures and standards, allows no room for any lapses in the above areas, produces estimates of high theoretical appreciation but often fails to gain user's confidence due to its variation from the ground realities. Since the broad objective of this study is to quantify the field reliability of the engines, we cannot neglect the above aspect. Therefore we adopt a method to identify the failure modes of an aeroengine through the failure space exploration based on the operational experience covering over five lakh hours of flying. This approach allows a hierarchically structured system with different layers by decomposition of sub systems into basic components. In this study, we focus our attention on top level system failures which are obtained by the agglomeration of elemental components of common group characteristics as illustrated in the next section.

5.0 CONSOLIDATION OF ACTIVE FAILURE MODES

Development of a system model to support reliability estimation begins with identifying the system configuration. This is often achieved by decomposing and then integrating the system keeping the needs of the particular analysis in view[17]. Collins [7] has described different mechanical failures based on the characteristics of the manifestation of failure, the failure inducing agent and the location of failure. Iren et.al.,[8] provides an account on the state of the failure mode taxonomy and the importance of study on the potential failure modes based on the mechanism of failure. In this study, a procedure similar to the component-failure matrix based on the repair types performed on the system has been adopted. During decomposition, we identify the components which cause the system failure and in the integration process, these components failures are connected to the system failure through a logic tree as done in fault tree analysis. The basic steps taken for the system decomposition and arriving at a reliability block diagram for the engine are given below:

- Identify the components responsible for the system failure and replaced during the subsequent repair at the maintenance depot.
- Based on the repair, identify significant clusters which got `renewed' as a result of repair.

- Build a logic tree indicating the effect of these clusters on system reliability.

- Evolve the Reliability Block Diagram at the engine level.

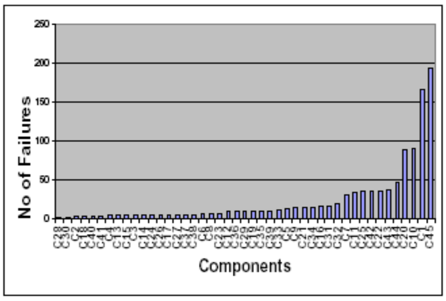

Figure 4. Frequency of Failure of components

The engine after declared `failed' in level 1 (figure 2), is sent to the repair depot (level 2) for the necessary repair and rectification. The activities in level 2 are shown in figure 3. Level 2 provides vital data in the form of individual failure reports for the analysis of in-service reliability. These failure event information need to be further processed and interpreted to establish the failure mode and effect of the failure on system operating state. The data base for this study consists of four sections such as:

1. **Inventory Data** : Details on the design and functional characteristics including identification of the engine.

2. **Failure Event Data** : Details of each failure including symptom of failure, circumstances of failure etc.

3. **Operating time Data** : The operational time (flying hours) and date of commencement of operation, date of failure etc.

4. **Repair Data** :This includes details of repair action performed such as component replaced, clusters which got `renewed' as a result of repair, repair duration etc.

From the field experience we could find that some of the components fail more frequently than others. Figure 4 shows the frequency of occurrence of 45 types of failures observed in this study. From figure4 we can see that five components (type of failures) contribute to 56.5 % of total failures and 82.55 % of the total failures are covered by 10 components. Remaining 35 components contribute only 17.45 % of failures.

Hence accounting for the failure data for all the 45 elementary components as separate entities may not be a wise approach as there won't be sufficient data to perform the statistical analysis for all components. Hence, on the basis of the engineering judgment, we group the elementary components of the mechanical assembly like compressor rotor, combustion chamber, turbine rotor etc into different clusters. Figure 5 shows the frequency of occurrence of the repair of these clusters.

This classification, based on the engineering analysis of the engine, not only helps to group the components of similar mechanical assembly but also to group the components having similar kind of environment and loads acting on them. This grouping gives rise to 10 different clusters of components indicating 10 different types of failures. In this study we refer to the type of failure modes and type of repairs synonymously since each type of failure is repaired accordingly and hence there is a one to one mapping between type of failures and type of repairs.

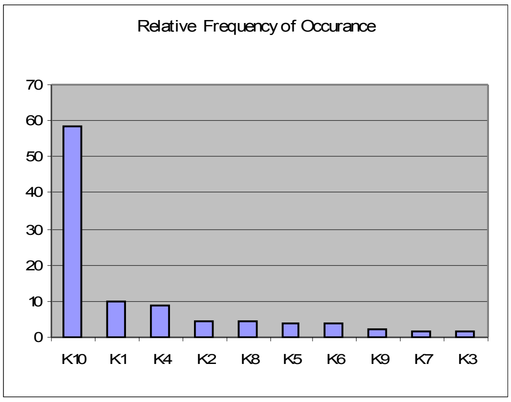

Figure 5 Relative Frequency of Repair of Cluster

6.0 DETERMINATION OF THE RELIABILITY STRUCTURE

Reliability topology is the relationship between the failure of an individual component to the failure of the aggregate system and it is determined based on the influence of individual failures on the system reliability. Having grouped the failure modes into different clusters, we need to evaluate the impact of each cluster on the system operation. System operational status conditional on the failure of each cluster has been evaluated to find the reliability wise structure of the system.

As part of the strict field maintenance practice for aeroengine, keeping the flight safety issues in view, the engines are withdrawn even at the occurrence of the symptom of failure. This generally leads to a condition where failure of any cluster / component results in the withdrawal of the engine impaling a `series' topology. The engineering analysis of the system structure also supports the series arrangement of different clusters. Once the reliability wise relation between each of the cluster is known to have a series structure, we can further group these clusters into modules without loosing any information of the system characteristics. The general scheme of evolving the system reliability structure is shown in Figure 6.

Cluster/ Module	M1	M2	M3	M4
K_1	x			
K_2	x			
K_3	x			
K_4		x		
K_5		x		
K_6			x	
K_7			x	
K_8			x	
K_9				x
K_{10}				x

Figure 6 The Scheme for System Level Consolidation

The series relationship allows us to have an extendable arrangement at each level. ie, failure of any of the components will cause failure of the respective clusters and failure of any such clusters will cause the corresponding group (say *Module*) to fail and this will cause the system to cease its function. In this configuration, the component with the smallest reliability has the biggest effect on the system's reliability. In addition, the weakest cluster/component dictates reliability of the engine.

In order to have a top level view on the system structure, we further consolidate the failure modes (repair actions) as indicated in figure 7 into four major sections (hence forth we denote them as `modules' in this paper). Each module can be considered as an independent sub tree of the logic diagram shown in figure 7.

Aeroengine being a safety critical system, repair procedure consists of replacement of the failed component and a thorough refurbishment of the connected parts ie., the cluster also. Similarly any malfunction of an item or any suspicion of malfunction will also lead to a through investigation and refurbishment of the affected area. Though identification of modules refers only to the tree structure, in this particular case we could find some mechanical characteristics also associated with these four modules as indicated below:

Module M1: This module includes all the components in the rotor assembly encompassing compressor rotors, turbine rotors and other dynamically loaded components like shafts. Repair or replacement of any of these elements necessitates re-balancing the rotor assembly.

Module M2: This module includes those components which serve as the interface between the rotating and static components. Bearings and seals of the engine are the members of this module.

Module M3: The major elements in this module are casings of air intake, compressor, turbine; stationary components in the flow path such as diffuser, combustion chamber, nozzle guide vanes, exhaust cone and other static accessories of the engine.

Module M4: In addition to the major items listed above, other miscellaneous failure modes which leads to the engine removal from the aircraft are included in this module.

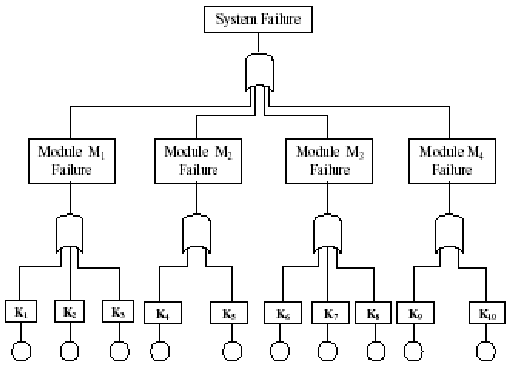

Figure 7 Structure of the Failure Modes of the System

The failure logic of system shown in figure 7 indicate the relationships between the modules of the engine. A system level reliability block diagram, expressing the way components are reliability-wise arranged in the engine is shown in figure 8.

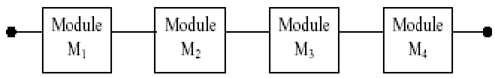

Figure 8 Reliability Block Diagram For the System

The main difference between our approach and the conventional design methods is that we distinguish the reliability wise hierarchy determined by the failure logics from the conventional decomposition hierarchy based on the system architecture. Reliability wise hierarchy leads from the top event of engine failure down to the component responsible for the engine failure, whereas the function based models start from the elemental component and trace up to the function which is getting disabled due to the component failure.

Based on the reliability block diagram developed in this section we can further evaluate the expected number of failures experienced by an engine during its mission time, instantaneous probability of failure at any given point of time during this period, the effect of elongating the mission time etc. For further analysis, the basic data to be extracted and tabulated is discussed in the next section.

7. 0 DATA EXTRACTION

As illustrated in section 2, the engine after being declared as failed to perform its intended functions, is removed from the airframe and sent to the repair depot for necessary repair. After performing the repair action, the system is subjected to an *`acceptance test'* to ensure its performance and to confirm the adequacy of repair. Therefore we can assume that repair of a component is equivalent to a *`part replacement'* in a *`socket'* according to the non-repairable system terminology. Therefore the counting process, which counts the number of service interruptions due to failure of the component in a socket, is a renewal process and hence the number of failures in each component socket can be reasonably modeled using a renewal process. For the system with *`k'* such sockets, the stochastic process is a super imposed renewal process.

7.1 Competing Risks: The system is conceptualised (as indicated in the RBD of section 6) in such a way that failures of four modules are the competing risks to terminate the current service life. The module failure observed is the risk which succeeded in terminating the current service life of the system, while other module failures are censored. Hence the first failure mode is explicitly seen and the risks, which might have killed the system a little later, are not explicitly observed. Let M_1, M_2, M_3 and M_4 denote the four modules and X_is denote the inter arrival times of M_i, $i = 1..4$, viewed as renewal systems. A repair, consists of the renewal of M_i and we get an exact observation on X_i and a censored observation on X_{j+}, $j+ = \{1...4\}- \{i\}$. Therefore, a typical scenario involving `n' observations will consist of `m' exact observations of the failure times and (n-m) censored observations. ie, the data is of the following form: X_1, X_2, X_3...X_m, X_{m+1}, ...X_{n-1}, X_n where X_i: i=1....m are the exact observations of the life time and X_i: i=(m+1) .....n are the censored observations where the exact lifetime is not known. Hence we adopt the following structure for the life data of each component.

Z = Min[X, Y]; I[z=x] where

X : Failure times of the module,

Y : Censoring times of the module

7.2 An Illustration: A typical illustration of a system released to service at *`starting time'* equals 0 and withdrawn from service at *`terminating time'* equals T* is shown in figure 9. Let T_{ij} denotes the system time at i^{th} modules' j^{th} event. Therefore the inter-arrival time X_{ij} of i^{th} module corresponding to the interval between j^{th} and $(j-1)^{th}$ events is given by $X_{ij}= T_{ij} - T_{i(j1)}$. The initial condition T_{i0} where i=1...4 is set as zero which is the *`starting time'* of the system. Similarly T* is the time of the final event for all modules M_1 to M_3. In the example shown in figure 9, the system suffers from two interruptions due to failure of modules M_1 and M_3.

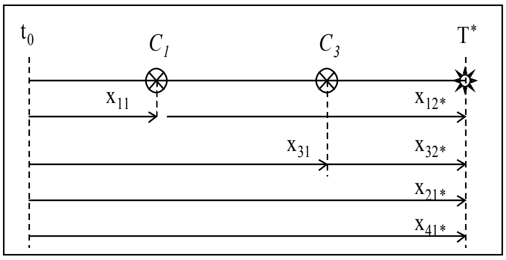

Figure 9 Observation on a Typical System.

First failure of module M_1 occurs at T_{11} and first failure of module M_3 occurs at T_{31} respectively. Therefore we get exact observations on X_{11} and X_{31} as $X_{11}= T_{11} - T_{10}$ and $X_{31}= T_{31} - T_{30}$. All other X_{ij}s viz $X_{12}= T^*- T_{11}$, $X_{21}= T^*- T_{20}$, $X_{32}= T^*- T_{31}$ and $X_{41}= T^*- T_{40}$ are censored.

Further discussion on the validation of data, verification of iid (independent and identical distribution) assumption, failure rate modeling etc. are presented in [6] and hence not presented in this paper.

8.0 CONCLUSION

In this paper, identification of basic reliability structure of the physical system and extraction of data for the reliability evaluation are illustrated. We emphasize the need for study on failure mode identification and data preparation as prerequisite for the reliability analysis. In this study we employ the information on field failure and the subsequent repair for identifying the failure pattern of an aero engine. Based on the failure history and the system knowledge, a reliability block diagram is developed and the data for in-service reliability evaluation is extracted using a competing risk set up.

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REFERENCES

[1] Allen Atamer, Comparison of FMEA and Field Experience for a Turbofan Engne with Application to Case Based reasoning. Proce IEEE Aerospace Conference 2004, pp 3354-3360.

[2] Albert L Selling, F 404 Engine Reliability program, SAE Technical paper No. 831539, Oct 1983.

[3] Andera Prencipe, Modular Design and Complex Product Systems : Facts, Promises and Questions. CoPS Publication No. 47, May 1998.

[4] J D Andrews and T R Moss, Reliability and Risk Assessment, Professional Engineering Publishing, UK, ISBN : 1860582907.

[5] Ascher and Feingold., Repairable systems Reliability, Modelling, Inference, Misconceptions and their Causes, Marcel Dekker,Inc New York. (1984) ISBN 0-8247-7276-8

[6] Chiranjit Mukhopadhyay, Mathews P. Samuel, Failure rate Modelling and Estimation of a Repairable Series System, IMT-GTR Conference on Mathematics, Statistics and Applications, Penag, Malaysia, June 13-15, 2006.

[7] Collins, J. A., B.T Hagan, and H.M.bratt, Failure - experience matrix: A useful desigh tool, Jl of Engineering for Industry, Aug. 1976, pp. 1074-1079.

[8] Irem Y. Tumer, Robert B. Stone, David G. Bell, Requirements for a failure mode taxonomy for use in conceptual design, int. Conf Engineering Design,ICED 03, Stockholem, Aug. 19-21, 2003.

[9] John Ferrie, Developments in Military Aero Engines, Proce. Int Seminar on Futuristic Aircraft Technologies, Dec 1996, IISc, Bangalore, India.

[10] H Langseth, B H Lindqvist, Competing Risks for Repairable Systems, Jl. Statistical Planning and Inference, 136 (2006) 1687 -1700.

[11] Mark Brown, Frank Proschan, Imperfect Repair, Jl Applied Probability, 20 (1983) 851-859.

[12] D. W Newton, Some Pitfalls in Reliability Data analysis Reliability Engineering and System Safety, 34 (1991) 7 - 21.

[13] Roger Cooke, Tim Bedford, Reliability Ddatabases in perspective. IEEE Transactions on reliability, volume 51, No3, sept 2002.

[14] Srikesh G. Arunajadai, Robert B. Stone, Irem Y. Tumer, Failure mode identification through clustering analysis. Proce. IMECE 2002, ASME Int. Mech Engg Congress 2002, Nov. 17-22, 2002, New Orleans, LA.

[15] Steven Kemta, Kosuke Ishii, Scenario-Baseed FMEA : A Life Cycle Cost perspective, Proce. ASME Design Engineering Technical Conference Sept 10-14, 2000, Baltimore Maryland.

[16] W A Thompson, On the Foundations of Reliability, technometrics, Vol 23, No.1, Feb 1981.

[17] Ulrich K T, The Role of Product Architecture in the manufacturing Firm, research policy, Vol 24, 1995, 419-440.

[18] Applying the Design Structure Mtrix to System Decomposition and Integration problems : A Review and New Directions, IEEE Transactions on Engineering Management, Vol 48, No. 3, Aug 2001 pp. 292-306.

[19] M. Xie, S L Ho, Analysis of repairable System failure data using time series models, Jl Quality in maintenance Engineering, Vol 5, No.1, 1999, 1355-2511.