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Graphical Techniques for Managing Field Failures of Aircraft Systems and Components

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This paper presents an application of graphical techniques based on cumulative and mean cumulative function plots for extracting management information from field failures of aircraft systems. Monitoring field failures is very important for aircraft operators who carry out in-house maintenance as well as for companies who provide maintenance services to the operators on a contractual basis. Very valuable information can be obtained from field failure analysis which will aid in tailoring the maintenance services in accordance with the operator's own local deployment, environmental and operating conditions. Analysis based on field failures is also very desirable for manufacturers, because the information received from the field gives a true measure of product performance and points out the areas of improvement to refine the product by design changes. Reliability practitioners usually attempt to analyze failures of aircraft systems with sophisticated statistical methods. Management and engineers who maintain and support the systems are easily intimidated by such intricate methods. Monitoring the failure of aircraft systems does not necessarily require complicated methods. This paper indicates a few simple but very powerful plots that help in tracking field failures of aircraft systems with an example of an air cooling system application. The plots based on mean cumulative function allow for measuring and monitoring system failures and maintaining statistical rigor without resorting to complex stochastic techniques. It is easily understandable by management and engineers, and enables them to quickly identify failure trends and unusual behaviors, compare different subsets of systems, reveal hidden information and gain insight.

I. Introduction

AIRCRAFT maintenance activities form an essential part of airworthiness. The common objective of a maintenance program is to prevent deterioration of the inherent design levels of reliability and operating safety of the aircraft at the minimum practical costs [1]. Today airlines operate in one of the most competitive business environments in the world with very small profit margins. For the present, maintenance costs of aircraft make a significant contribution to an aircraft's operating costs. Unscheduled maintenance tends to be more costly than scheduled maintenance because it is unplanned. Therefore, operators seek every possible means to reduce unscheduled maintenance and downtime of aircraft.

Regulations require every aircraft operator to have a maintenance schedule. The maintenance schedule sets out the what, how, and when of the operator's scheduled maintenance effort. It includes a specific list of each individual maintenance task and its associated time limit. Individual scheduled maintenance tasks are usually grouped or packed into integrated scheduled work packages to simplify administration and control, and provide a continuous succession of necessary or desirable scheduled maintenance tasks for the entire aircraft. These work packages are usually identified as letter checks such as A, B, C, and so on, and generally scheduled at successively longer intervals. However, for the same letter check the actual tasks performed may differ greatly from one scheduled visit of aircraft to the next. Hence, the letter-check designation terms A1, A2, B1, B2, C1, C2, etc., are used. Manufacturers customarily express time intervals for letter-check packages in flight hours and cycles. However, primarily for the convenience and ease of scheduling, these time intervals may be converted to calendar time intervals based on average daily usage of the aircraft by the operator.

An operator's maintenance schedule is initially produced by the manufacturer. Although an operator follows the maintenance planning document and time intervals dictated by the manufacturer, it is quite likely that it would still experience many unscheduled maintenance actions or may suffer from long turnaround times on scheduled tasks. The maintenance schedule recommended by the manufacturer governs the operator's initial maintenance policy. It needs to be revised over time by redistributing maintenance task items to the appropriate time intervals based on the operator's particular operating schedule and environmental conditions, maintenance capabilities, and experience gained, so that the unscheduled element of maintenance is exchanged for more scheduled maintenance. Of course, this does not relieve the operator or civil aviation authority of their responsibility for the effect of the schedule on safety. The purpose of these revisions is to enable the operator to develop appropriate inspection or replacement schedules and spare part plans that best suit the particular maintenance organization and operating environment enhancing maintenance efficiency in a cost-effective manner without impairing the airworthiness of the aircraft.

Many aircraft operators carry out maintenance activities in their in-house facilities by themselves. However, there is a growing trend of operators outsourcing their maintenance. Recently, aircraft operators often rely on third-party maintenance providers who are not necessarily the original equipment manufacturers (OEM) to perform a variety of maintenance tasks. The work that is outsourced varies widely in scale and in scope. Because of perceived increase in demand for third-party maintenance services, the number of vendors that are usually referred to as MRO (maintenance, repair, and overhaul) companies continues to grow [2]. This strongly points out that aircraft maintenance is no longer just a business between the operators and OEMs; it is moving toward an open and competitive MRO business. The primary driver behind the growing acceptance of MRO companies by operators is the significant cost savings they deliver. MRO companies offer a broad range of maintenance services (servicing a particular component or a system, overhauling an engine, or performing some letter checks for the entire fleet of aircraft) to commercial, business, regional, and military aircraft

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operators in diverse locations. To survive and evolve in this highly competitive and dynamic market, MRO companies should monitor the operations at their customers' sites, find out easy and understandable methods for exchanging technical information, and respond quickly with unique maintenance solutions which are tailored to each customer's particular, ever-changing maintenance requirements. Any decision to be made regarding changes in maintenance policy, mainly relating to the time interval between consecutively scheduled inspections or replacements of life-limited parts, should be based on a rational, quantifiable, and understandable methodology for monitoring and analysis of field failures. This is an important requirement for shaping any maintenance management program.

Analysis of failure data for the fielded systems is also very important to the manufacturers. Because of high reliability of modern products and short product development time, it is often not feasible to verify the reliability of a product by testing. Therefore, field failure analysis becomes more important for measuring the real reliability of various products. Recently, part manufacturer approval (PMA) suppliers who produce Federal Aviation Administration/European Aviation Safety Agency approved replacement parts for the aircraft and engines have been gaining a stronger acceptance by the aircraft operators and MROs as an alternative to OEMs in the aftermarket area. The reason behind this shift is not only the lower price of the PMA part itself. When an OEM is not responsive to its customers' problem (related to a part or a system), it leaves itself open to the competition from PMA suppliers who fill the gap by designing product improvements or fixing a problem part that an OEM is unwilling to address. In such cases, operators or MROs switch to PMA suppliers who offer customized parts, because it helps them to lower their operating cost further by reducing the recurrent inspections or replacements and turnaround time due to that specific part. These specific design improvements or fixes require analysis of field failure data for the relevant part, because the information received from the field gives a true measure of product performance and points out the areas of improvements to refine the product by design changes. Therefore, analysis of failures from the field has gained a central importance for manufacturers too. It is preferable that the methodology to be selected for field failure analysis is simple, fast, and statistically valid so that it allows manufacturer's management to easily see how their products perform compared with competing products and to estimate cost of guarantees, and to provide design teams with feedback on design margins and information on reliability growth.

In terms of the failure analysis, any aircraft is a complicated system. It is composed of many subsystems. Each subsystem is formed by subunits at a lower level. The failure analysis practitioners often attempt to model such systems with sophisticated statistical methods such as a nonhomogenous Poisson process (NHPP) and maximum likelihood parameter estimators (MLE). Furthermore, the failure analysis is made more difficult by the highly multicensored nature of data. Management as well as engineers and field service teams who maintain and support aircraft systems are easily intimidated by such complex techniques. Hence, it is very important to employ a failure analysis methodology which is statistically valid, yet *speaks* to the managers and engineers in the professional language with which they are familiar.

Monitoring failures of the complex systems does not necessarily require complicated methods. Graphical methods based on the mean cumulative function (MCF) [3–7] allow for monitoring system failures and maintaining statistical rigor without resorting to complex stochastic techniques. It is simple, easy to understand, prepare, and present. It can be successfully used to track field failures and identify failure trends, anomalous systems, unusual behaviors, effects of various parameters (maintenance policies, environments, operating conditions, etc.) on failures, and so on. Thus, it is a significant decision support tool which permits the operators, maintenance providers, and manufacturers to make quantifiable and rational decisions in the field that had typically been the domain of guesswork and experience. This extremely useful and simple concept has been in existence for nearly two decades, but the literature remains highly theoretical for the average practitioners, and reported applications have been very limited [7,8]. Particularly, there is no reported application in relation to the aviation industry. This paper illustrates the application of the graphical method to present effective field data analysis methodologies for aircraft systems and components. In the practical example presented here, it will be shown how valuable information can easily be extracted from field data by application of the method. Though the discussion is presented here in the context of the air cooling system, the techniques covered are general in their applicability.

The remainder of this paper is organized as follows: A brief description of the air cooling pack is presented in the next section. Sect. III describes cumulative plots and MCF methodology. In Sect. IV the data used in the study are presented with explanations. Sect. V indicates application of simple plots for analyzing field failures of the air cooling pack at the system and component level, and explains how to use and interpret such plots. Finally, the paper is concluded in Sect. VI.

II. Aircraft Cooling System Characteristics

Aircraft air cooling systems are important; they feed the cabin with cool air at a certain temperature. There are mainly two types of air cooling systems used in aircraft: the air cycle machine cooling system and the vapor cycle machine cooling system. However, the air cycle machine is the predominant means of air cooling for commercial and military aircraft of all types and this type of cooling system is investigated in this paper. The aircraft air cycle machine cooling system uses the high-pressure bleed air extracted from the engine compressor or auxiliary power unit. The cooling system consists of the following subsystems: air conditioning/bleed air control panel, flow control and shutoff valve, heat exchangers (HE) (two), air cycle machine, ram air system, water separator (WS) and low limit (35°F) system. These subsystems are composed of subunits or components at a lower level. The air conditioning/bleed air control panel gives controls and indications of the cooling system. The flow control and shutoff valve is electrically controlled and pneumatically actuated. It controls the airflow to the cooling pack. The heat exchangers are air-to-air, plate fin, crossflow types. There is both a primary heat exchanger and a secondary heat exchanger. They remove the heat from the air at different stages of the cooling cycle. The ram air system controls the quantity of outside ambient air that flows through the heat exchangers. The air cycle machine (ACM) is a high speed rotating machine. It has a compressor, turbine, and impeller fan connected by a common shaft. Air bearings support the shaft and let the ACM turn at high speed with little friction. The function of the ACM is to decrease air temperature by expansion through the turbine. The water separator is a cylindrical chamber with a taper at the upstream end. The coalescer bag in the water separator collects water mist from the air. It also helps prevent damage from ice or debris that may be present in the air. The low limit (35F) system monitors and adjusts the temperature in the water separator to prevent water freezing conditions. The system uses a temperature sensor, a controller, and a valve to perform its function. The operation cycle of the cooling system is as follows: Bleed air from the pneumatic system supplies bleed air to the flow control shutoff valve. After the bleed air goes through a flow control shutoff valve it enters the primary heat exchanger. As the bleed air goes through the heat exchanger, ram air removes heat. The cooled bleed air then enters the compressor section of the air cycle machine where the air is compressed and temperature increased. The compressed air then goes to a secondary heat exchanger for additional cooling and back to the turbine section of the air cycle machine where it is cooled by expansion. Next the air goes through a water separator. The water separator collects and removes moisture from the air before it goes into the distribution system.

III. Cumulative and Mean Cumulative Functions

There are various methods for failure modeling at different levels. The distributions based on the Weibull family are the most commonly used models for analyzing failures at the level of individual components that are replaced by the new components when they fail. However, a distribution, such as the Weibull distribution, which uses renewal theory, cannot be used to estimate the failure pattern of a system which is not replaced but repaired when it fails. To address the failure characteristic of a repairable system, a process is often used instead of a distribution. The most popular process model for repairable system analysis is the power law model. As the Weibull distribution addresses the very first failure, the power law model addresses each succeeding failure for a repairable system. Both of these powerful parametric methods require estimation of parameters using some rigorous statistical methods such as the MLE which makes them too complex for communicating with management, engineers, and customers.

Another method for analyzing failures is the usage of a nonparametric approach. Average practitioners relate more easily to the nonparametric approach compared to indiscriminate modeling with various distributions. Graphical techniques based on plotting cumulative failures and MCF provide a nonparametric method [9] for analysis of field failures. This simple and very efficient method has an advantage of being appropriate for failures both at the component and system levels. It requires minimal assumptions and uses cumulative and MCF plots which are easily understandable for management. A cumulative plot is a plot which indicates the number of failures over time for a single system. Time can be hours, days since commission of the system, calendar time, or cycles. Cumulative plots are useful for showing trends in the occurrence of failures or repair events. MCF is the average of the cumulative plots across all the individual systems at risk at any point in time. It simply represents the average number of failures that can be expected at various ages of a system in the population and enjoys all the properties of a cumulative plot such as revealing the average failure trends of the population of systems in the organization.

In this method, usually the failure data of each system is first plotted against calendar time including downtime which produces cumulative plots over calendar time. To obtain cumulative plots over operating time the data then are transferred from calendar time to operating time by removing the downtime of each system. Next, it may be necessary to determine the number of systems at risk as a function of operating time. Then, the mean cumulative function is calculated and plotted against operating time. MCF is calculated at each failure by using a recursive formula [5] with an implicit assumption that one and only one failure can occur in a single time period:

$$\mathrm{MCF}\,(t_i) = \mathrm{MCF}(t_{i-1}) + \frac{1}{N(t_i)} \tag{1}$$

$N(t_i)$ is the population at risk at time t_i, that is, the number of systems in use at time t_i. Note that Eq. (1) allows for a decreasing population, so right censored data involves no extra calculation in MCF plotting.

MCF is a nondecreasing stepwise function. From the corresponding continuous MCF it is possible to find and plot the recurrence rate (RR). Recurrence rate is the slope of the MCF curve and represents the number of failures per unit time. It is also called rate of occurrence of failures. The recurrence rate plot magnifies the trends in the MCF curve and identifies portions of age or calendar time where the rate of occurrence of failures is increasing or decreasing. A curvature with increasing slope indicates an increasing recurrence rate with age which means that the underlying system is deteriorating with time. A curvature with decreasing slope indicates a decreasing recurrence rate which points to an improving system with time. A straight line indicates a constant recurrence rate which represents a random failure pattern with no trend.

Another term for recurrence rate is the failure intensity, but this may cause confusion with the quite different failure rate (hazard rate) of a life distribution for nonrepaired units (components that fail once). Even though they have the same units (number of failures per unit time), recurrence rate should not be confused with the failure rate. However, in the case of exponentially distributed component lifetimes, the failure rate is constant and recurrence rate is equal to the failure rate.

It is possible to give a good approximation to the pointwise confidence limits of the MCF values. The approximated upper and lower confidence limits [10] for every observed MCF value are as follows:

$$\mathrm{MCF}^-(t_i) = \mathrm{MCF}(t_i) - U_{1-\frac{\alpha}{2}}\sqrt{V(t_i)} \tag{2}$$

$$\mathrm{MCF}^+(t_i) = \mathrm{MCF}(t_i) + U_{1-\frac{\alpha}{2}}\sqrt{V(t_i)} \tag{3}$$

Here $U_{1-(\alpha/2)}$ is the $1-(\alpha/2)$ percentile of the standard normal distribution. For 80, 90, and 95% confidence limits, it is 1.28, 1.54, and 1.96, respectively. $V(t_i)$ is the variance of the cumulative number of failures per system at t_i and can be computed recursively by

$$V(t_i) = V(t_{i-1}) + \frac{1}{N^2(t_i)} \tag{4}$$

The confidence intervals are to be understood more as an envelope of pointwise confidence intervals on the mean rather than a prediction or tolerance interval on the MCF. Thus, if a system falls within the limits, it is definitely not an anomalous system. However, if it falls above the upper confidence limit then visual interpretation or heuristics are used to determine if the system is experiencing a higher number of failures than the population. This approach works quite well in most practical situations (particularly in smaller sample sizes) without resorting to exact computation of prediction intervals.

IV. Failure Data

The data analyzed here were obtained from a local aviation company in Saudi Arabia and for the air conditioning/cooling packs installed in a very popular aircraft. The aircraft is used by most of the airlines around the world. The way airlines maintain and support their fleets is rather sensitive information. To respect the sentiments of the airline, aircraft, and component manufacturers, their names are not disclosed and a few years of old failure data are used. The data were collected from maintenance records of the company over a period of about five years. Air cooling system failures are the main in-service issue for the company. The aircraft were new as of the beginning of the data collection. There are three aircraft with registration numbers N737A, N738A, and N739A. Each aircraft has two air cooling packs, right and left. For convenience, aircraft are named in serial order from X to Z. Air cooling packs are numbered as 1 to the left and 2 to the right. Thus, for example, X2 refers to the right air cooling pack in aircraft N737A. The data have the following entries: routine/nonroutine work, aircraft registration number, description of reported fault, Air Transport Association (ATA) chapter number, part number, date, description of corrective action, aircraft total time, aircraft total cycles, total man hours, and engine parameters (if applicable). Table 1 shows summarized failure data related to aircraft Z. There are similar failure data records for each aircraft. In this study, a failure is defined as degradation below a defined level or limit set by the manufacturer's specifications. Maintenance records were reviewed in detail for the air cooling pack failures. This enabled the determination of whether a field removal was a confirmed failure or a "No fault found", thus eliminating false removals in the data. A total of 232 confirmed failures were observed for all aircraft.

The company conducts scheduled maintenance and inspection services through preflight and postflight checks, A-checks, and C-checks in its in-house facilities. A-checks, which last 5 working days, are repeated every 4–5 weeks. C-checks are performed annually and take 4–6 weeks. During the periods of A-checks and C-checks, the aircraft is grounded. Maintenance task cards indicate that the air cooling system is maintained through appropriate letter checks under an "on-condition" maintenance process which requires inspections of certain subsystems or components. There is no "hard-time" maintenance process which requires periodic replacement of the components as life-limited items.

Table 1 Air cooling system failure data for aircraft Z

Left air cooling pack Failure no.	Failure time, flight hours	Component	Right air cooling pack Failure no.	Failure time, flight hours	Component
1	58.06	Water separator	1	93.53	Water separator
2	93.53	Water separator	2	265.28	Heat exchanger
3	118.08	Pack switch	3	381.82	Water separator
4	245.18	Water separator	4	479.64	Water separator
5	417.16	Water separator	5	628.82	Water separator
6	628.32	Water separator	6	810.25	Shutoff valve
7	677.68	Ram inlet	7	902.36	Water separator
8	816.58	Heat exchanger	8	1043.26	Ram inlet
9	953.54	Water separator	9	1194.38	Water separator
10	1082.46	Water separator	10	1316.76	Pack switch
11	1152.8	Shutoff valve	11	1498.77	Water separator
12	1316.34	Water separator	12	1556.84	Water separator
13	1421.28	Water separator	13	1593.28	Water separator
14	1503.1	Ram inlet	14	1700.92	Air cycle machine
15	1557.27	Ram inlet	15	1987.22	Water separator
16	1635.27	Water injector	16	2025.06	Water separator
17	1701.36	Water separator	17	2244.2	Water separator
18	1940.8	Water separator	18	2270.48	Low limit switch
19	2013	Water separator	19	2383.56	Air check valve
20	2102.38	Water separator	20	2458.67	Water separator
21	2128.42	Water separator	21	2538.18	Water separator
22	2208.64	Ram inlet	22	2801.43	Shutoff valve
23	2365.56	Water separator	23	2979.28	Water separator
24	2383.44	Air cycle machine	24	3011.22	Air cycle machine
25	2478.16	Water separator	25	3148.08	Water separator
26	2538.28	Water separator	26	3306.72	Water separator
27	2609.06	Heat exchanger	27	3635.05	Overheat switch
28	2801.26	Air check valve	28	3705.6	Heat exchanger
29	2935.28	Ram inlet	29	3775.45	Air cycle machine
30	3052.64	Water separator	30	3843.1	Water separator
31	3115.24	Water separator	31	4101.42	Water separator
32	3306.66	Air cycle machine	32	4111.76	Water separator
33	3479.8	Pack switch	33	4178.8	Water separator
34	3566.2	Water separator	34	4357.64	Air cycle machine
35	3635.18	Water separator	35	4402.64	Low limit switch
36	3812.32	Water separator	36	4503.78	Heat exchanger
37	3990.84	Air cycle machine	37	4592.2	Pack switch
38	4112.54	Water separator	38	4653.4	Water separator
39	4197.08	Water separator	39	4735.2	Water injector
40	4204.57	Water separator	——	——	——
41	4352.27	Water separator	——	——	——
42	4443.74	Air cycle machine	——	——	——
43	4545.08	Water separator	——	——	——
44	4602.7	Overheat switch	——	——	——
45	4638.9	Heat exchanger	——	——	——

The data were first analyzed at the system level, which is done by considering a system failure as any action taken when the pack is not operating properly and is serviced, and the particular components that have failed are ignored. In addition, analyses were undertaken with the most observed failures at lower level including subsystems/components (water separator bag, heat exchanger, and ACM). The failure data represent in-service failures, in other words unscheduled maintenance actions, which are the main concern of all operators.

The water separator is subject to periodic visual inspection at every 500 flight hours as recommended by the manufacturer. As dirt and contamination collect on the coalescer bag, air flow rate through the bag decreases. When the water separator indication disk is in the red range, the coalescer bag is replaced; otherwise it continues in service. Maintenance records reveal that water separator indicator inspections are conducted in A5, C1, A15, C2, etc. checks.

The heat exchangers are subject to a restoring maintenance task at every 2000 flight hours as recommended by the manufacturer, and the task is conducted in appropriate C-checks. The restoring task requires visual inspection and cleaning of primary and secondary heat exchangers.

The air cycle machine is subject to visual inspection and some special tasks such as turbine scroll housing measurement, removal of soft time, etc., at appropriate C-checks. No air cycle machine has yet reached the number of hours for overhaul.

V. Aircraft Cooling System Application

A. Graphical Analysis of Failures at the System Level

Figure 1 indicates the failures of six cooling systems as a function of calendar time. The line starts at the date the first aircraft (hence, the cooling systems X1 and X2) was put into use. The x marks failures and the spaces indicate the C-checks. The A-checks are not shown to prevent ambiguity in Fig. 1, but those checks are taken into account in further calculations. The failure data are then transferred from calendar time to flight hours in Fig. 2. Next, the number of systems at risk is determined as a function of operating time based on Fig. 2 to allow for calculating MCF and incorporating right censoring by accounting for the number of systems at risk at a particular age when failures occur.

Figure 3 indicates the cumulative plots for the population of six cooling systems under consideration over nearly 5000 flight hours. It can be seen that the growth in failures vs time for all systems is nearly linear which points to no trends in failures. The accumulated number of failures for each system at a specified time is read directly from Fig. 3. For example, system X2 has experienced 35 failures in 4800 h. The MCF for the population is then calculated by taking the average of the number of failures across all the individual systems at risk at each point of failure. Figure 4 indicates the MCF for all six cooling systems against flight hours where the steps have been replaced with

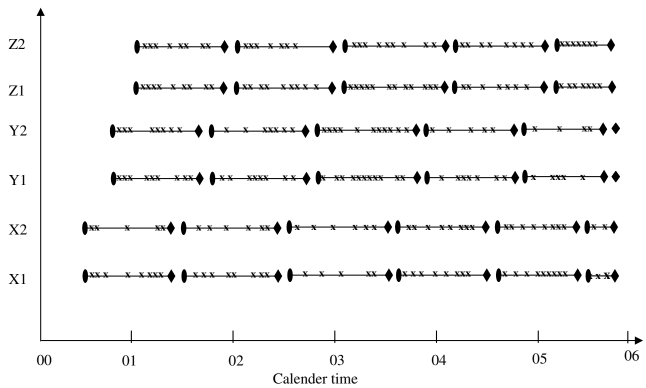

Fig. 1 Air cooling system failures as a function of calendar time.

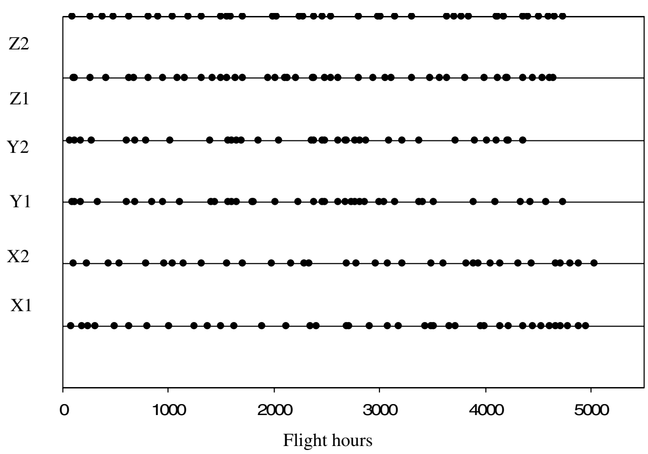

Fig. 2 Air cooling system failures as a function of flight hours.

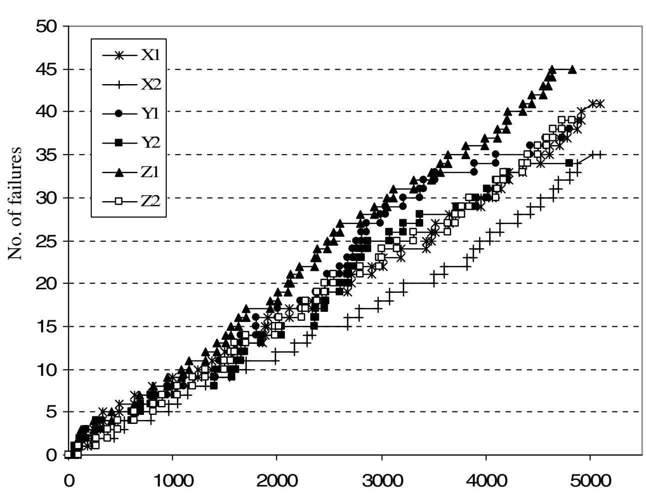

Fig. 3 Cumulative plots of air cooling systems.

connecting lines. It can be seen that MCF is increasing almost linearly and may be fitted very well ($R^2 = 0.9983$) with a straight line through the origin indicating that the recurrence rate is fairly constant. Therefore, the cumulative recurrence rate can be computed from the slope of the line as $\mathrm{RR} = 0.0079$ failures/h.

Calculating the MCF also allows an estimate of the population mean cumulative number of failures by some specified time, which can be read directly from the curve. For example, from Fig. 4 the estimate of this by 1000 flight hours (average flight hours per aircraft per year) is eight failures (on average) per air cooling system, an answer to the basic question. Because the recurrence rate is constant, one can expect 48 failures (or unscheduled maintenance actions) per year for the entire fleet due to air cooling packs.

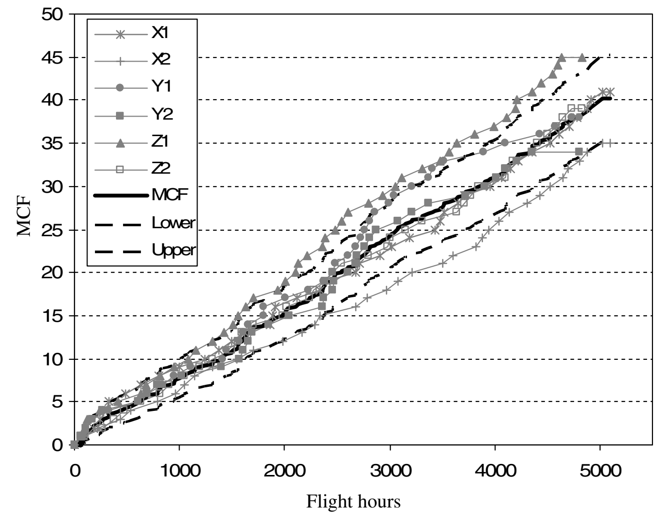

Fig. 4 Mean cumulative function with confidence intervals.

Figure 4 also shows the 95% confidence intervals of MCF for the six systems which can be used to identify anomalous systems. The cumulative plot of system Z1 goes slightly beyond the upper confidence level. Therefore, for engineering purposes, one can say that the system Z1 is experiencing a higher number of failures than the population at large. Visual inspection of data confirms that system Z1 is the system with the highest number of failures (45 failures) in the population. Further investigation of the maintenance records indicated that five out of seven ram air inlet failures over all air cooling packs have occurred in system Z1. This may suggest that the unusual behavior of system Z1 is likely due to its ram air inlet assembly problem.

One of the most useful capabilities of plotting MCF vs system age is that it can be used for comparing different populations of systems. It provides a way to compare the cumulative failures at various ages across different subpopulations of systems. In this case, cooling systems are installed in pairs on three aircraft. Each pair installed on the same aircraft is taken as a subset for further analysis. The MCF for each pair of cooling systems for three aircraft is shown in Fig. 5. Even though the pair of systems in aircraft Z has had the highest number of failures, it is still operating within the bounds for this population. Therefore, there is no anomalous aircraft from the point of air cooling pack failures. This simple technique allows the maintainers to monitor failures by aircraft tail numbers and to see if there are any unusual behaviors due to conditions such as system installation and integration, utilization, flight route, maintenance team specific to an aircraft or a group of aircraft, and then zoom in on the aircraft in

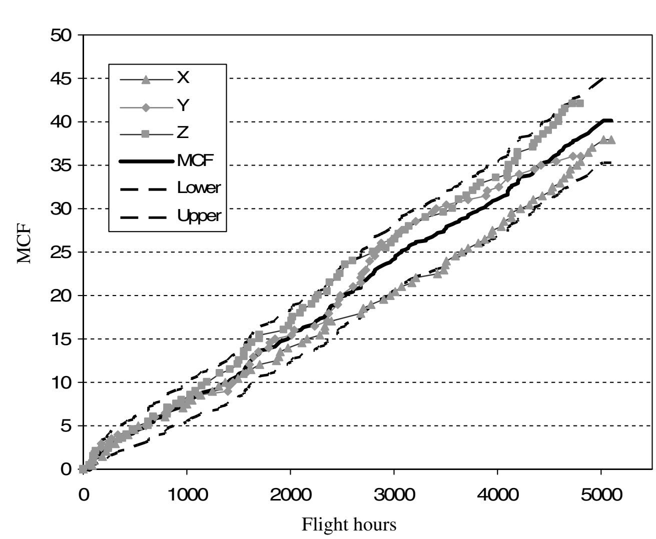

Fig. 5 Mean cumulative function for a population of three aircraft.

question. The same technique can also be used by an MRO company to compare different subsets of aircraft or systems in a more versatile way. The subsets can be aircraft/systems from different customers, sites, environments, operating conditions, maintenance policies, etc.

B. Graphical Analysis of Failures at the Lower Level

It is also possible to plot MCF for interesting subsystems, modules, or individual components to do a more thorough analysis and prioritize maintenance tasks. One of the standard plots used to depict the number of failures of various components is the Pareto chart. Figure 6 indicates failure frequencies across the air cooling systems. The water separator is the component with the most observed failures (141 failures). The air cycle machine has failed 21 times. The heat exchanger, which has failed 19 times, follows the air cycle machine. Other components have failed less than 10 times. It is evident that the Pareto chart is static in time and does not address variations in the number of failures over time. Cumulative plots are far more revealing because they are dynamic, showing time evolution of failures of components. Figure 7 indicates the flight-hour plot for the heat exchanger and air cycle machine relative to the Pareto chart in Fig. 6. In the Pareto chart, these components have almost equal contributions. However, in the flight-hour plot one can clearly see different trends in the occurrence of failures. For greater understanding, failures of these components are plotted for each system and then normalized by the number of systems akin to MCF in the next section.

Figure 7 also points to the need for careful usage of mean time between failures (MTBF) as a reliability parameter. The heat exchanger and air cycle machine have had almost the same number of failures (19 and 21, respectively) in almost 5100 h, resulting in an MTBF of about 255 h. Even though they have the same MTBF, there is clearly a difference in the behavior of these components. This difference is explicitly captured in the cumulative plot given in Fig. 7. Consequently, strict reliance on the MTBF without full understanding of the implications can result in missing developing trends and drawing erroneous conclusions.

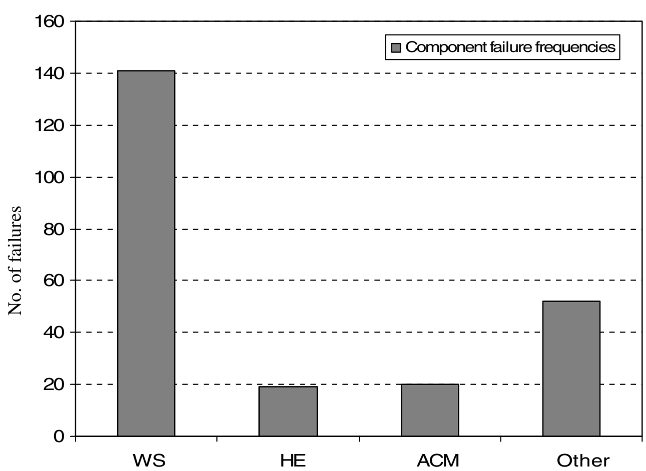

Fig. 6 Pareto chart showing component failures.

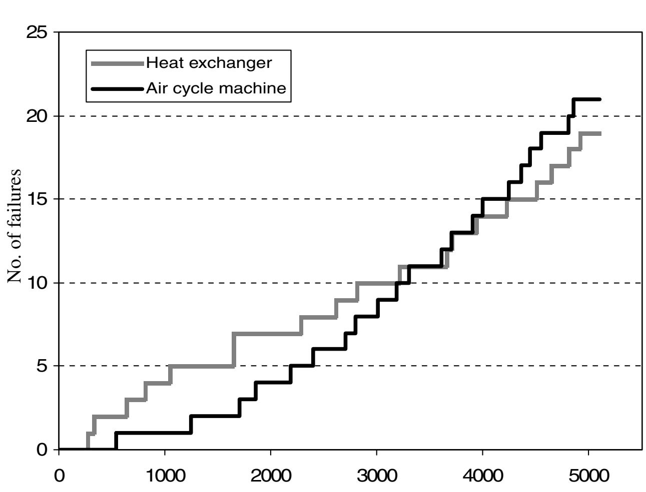

Fig. 7 Cumulative plots of heat exchanger and air cycle machine.

1. Water Separator Bag

The water separator bag is a component which is replaced when it fails. Failures of such components are usually modeled by using various distributions (such as Weibull) based on renewal theory. However, the graphical method presented here can also be used to analyze failures of such components and it is more understandable, faster, and simpler. Failures of the water separator on each air cooling pack are first analyzed over flight hours. Analysis is conducted for groups of failures over intervals of monthly flight hours by replacing $1/N(t_i)$ with $\Delta r(t_i)/N(t_i)$ in Eq. (1) where $\Delta r(t_i)$ is the number of failures that have occurred in the time interval between t_{i-1} and t_i. Figure 8 indicates cumulative plots and MCF with confidence bounds for water separator bags over flight hours. It is seen that MCF is changing almost linearly with flight hours; therefore, the failures seem to occur randomly with a nearly constant recurrence rate. MCF may be fitted very well ($R^2 = 0.9957$) with a straight line through the origin and the cumulative recurrence rate can be calculated as the slope of this straight line as $\mathrm{RR} = 0.0049$. Because the failures occur randomly, it points to an exponential life distribution for the water separator bag. Thus, it is expected that the recurrence rate calculated by the plotting method should be nearly equal to the failure rate computed by the Weibull method. The failure rate for the water separator bag using the Weibull method is 0.0046 [11]. It is clear that there is very good agreement between the two methods, but the advantage of the graphical method, from the point of simplicity, is very obvious.

It is possible to extract invaluable information from Fig. 8 as discussed in Sec. V.A. For example, in 1000 h of operation the water separator has failed 5 times on average per system. Therefore, one can expect that 30 water separator bags will be needed on average annually to service the entire fleet. However, one may want to protect against shortages and use something such as the 75, 85, or 95 percentile instead of the mean (50th percentile, assuming Gaussian distribution). Setting the appropriate number depends on the relative costs of being "short" vs having a surplus of water separator bags at hand.

Because the water separator bag failures follow a renewal process and the failure rate is constant, one can apply the conventional notion of MTBF which is estimated as 204.08 flight hours. The appropriate

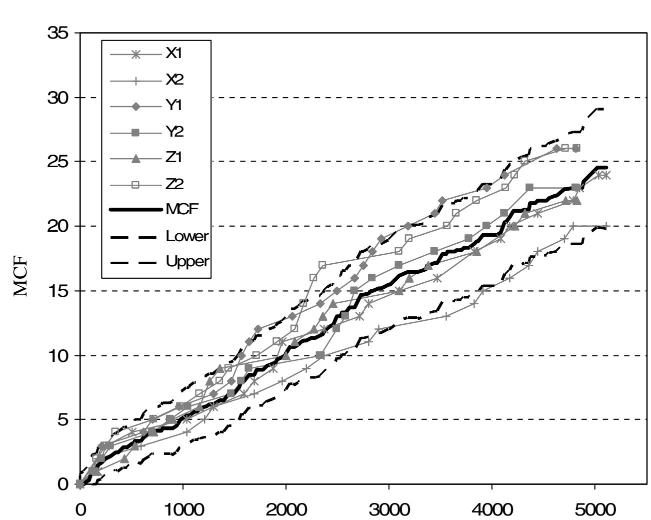

Fig. 8 Mean cumulative function for water separator.

response to a constant failure rate is to employ on-condition maintenance and develop an appropriate inspection and monitoring program. The manufacturer recommends a monitoring program with a visual inspection of the component at every 500 flying hours in an attempt to catch the next failure and reduce in-service failures. However, the result of the data analysis indicates that an inspection interval for this component is likely to be appropriate at about 200 flight hours, which is quite different than the time interval recommended by the manufacturer.

Although it is found that water separator bag failure occurs randomly, implying that failure is not age related, it may be useful to plot the variation of the recurrence rate over time to detect those intervals where the rate of failure occurrence is changing. Figure 9 indicates recurrence rate vs flight hours for the water separator for each cooling system. The local recurrence rate is estimated by numerical differentiation of the cumulative average number of failures vs age. The degree of smoothness of the curve is controlled by the number of points used in calculating the tangent at each point in the cumulative plot. Spreadsheets have a slope function which can be used to calculate the local recurrence rate. Figure 9 reveals that there is no trend in failures with flight hours. However, many distinctive spikes can be observed. These spikes indicate the intervals where multiple failures occur in a short period of time. Particularly, spikes at the beginning provide clues for potential early life problems for the water separators which may be caused by learning curve issues with the maintenance personnel. In fact, maintenance work forms indicate that maintainers have replaced water separator bags in a pair (left and right) as a corrective action in 13 cases in response to reported faults and nine of these replacements were carried out in the first 500 flight hours after each aircraft was commissioned. Although only one of the water separators has actually failed in these cases, it is likely that maintainers used the opportunity to replace the unfailed one in an attempt to prevent another failure. Therefore, these failures may be related to the learning curve issue.

Aircraft systems are subject to many effects during their operation. Some of these effects are not age dependent but are a result of external events which cannot be detected in an age-based analysis. To explore the impact of these hidden effects, it may be required to analyze failures over calendar time. Calendar time analysis is exceptionally useful for indicating trends in the rate of failures following letter checks, overhauls, component or system upgrades, and due to effects such as seasonal variations, changes in maintenance schedule or maintenance personnel, and so on. Figure 10 shows the variation of the recurrence rate for the water separator as a function of monthly calendar time. Distinct spikes can be seen in Fig. 9 that now align over an almost common period of time (March–April) in every year. This indicates that even though the water separator failure is not age related, it shows a seasonal trend which, most probably, can be attributed to variations in weather

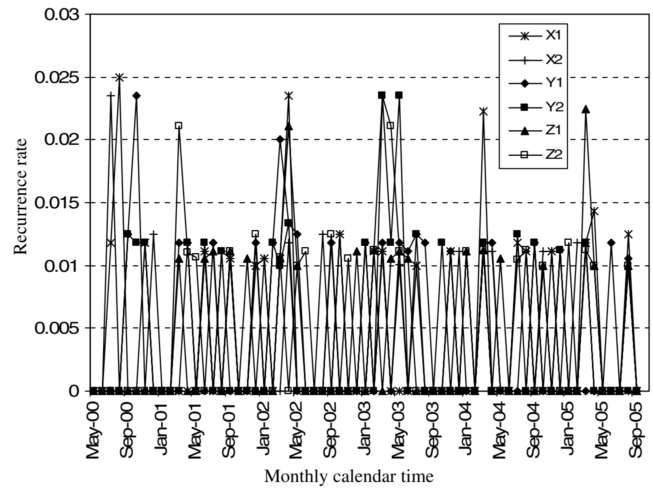

Fig. 10 Recurrence rate vs calendar month for water separator.

conditions (especially sand storms) during the year. At this point, one may consider it useful to plot cumulative water separator failures on a monthly basis to explore the effect of weather conditions on the rate of occurrence of failures. However, this approach would be meaningless for aircraft systems and components, because accumulated operating flight hours differ from one month to another and from one aircraft to another. Thus, instead of plotting cumulative failures, the monthly average recurrence rate of the water separator for the population of six systems is plotted in Fig. 11; therefore, the potential seasonal effect is investigated in more detail. The average recurrence rate per month is calculated as follows: First, the recurrence rate of each system is calculated for each month. For example, system Z1 has accumulated 360 flight hours and experienced one water separator failure in December from the date aircraft Z was commissioned to the date data collection was terminated. This produces a recurrence rate of 0.00278 in December for system Z1. The same procedure is repeated for each system. The average monthly recurrence rate in December is then calculated by taking the average of calculated recurrence rates over six systems. Figure 11 indicates very clearly that the water separator fails at the highest rate (0.0108) in March which is likely the period of most adverse weather in the region. April and May follow with recurrence rates of 0.0093 and 0.0052, respectively. June is the month with the lowest recurrence rate. Figure 11 implies that recurrence rate is not constant during the year. Therefore, a two-state analysis [12] may be considered to enable a more accurate forecasting of failures. Let the recurrence rate during spring (adverse weather) be λ_a and during the rest of the year (normal weather) let it be designated by λ_n. Adverse weather is present during a fraction T_a of the year and normal weather

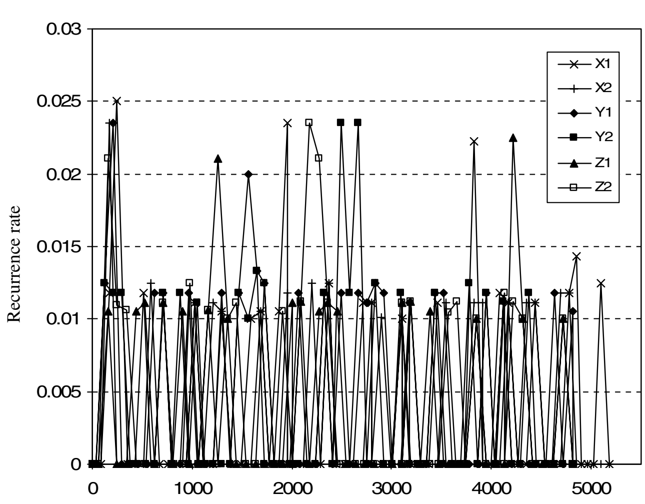

Fig. 9 Recurrence rate vs flight hours for water separator.

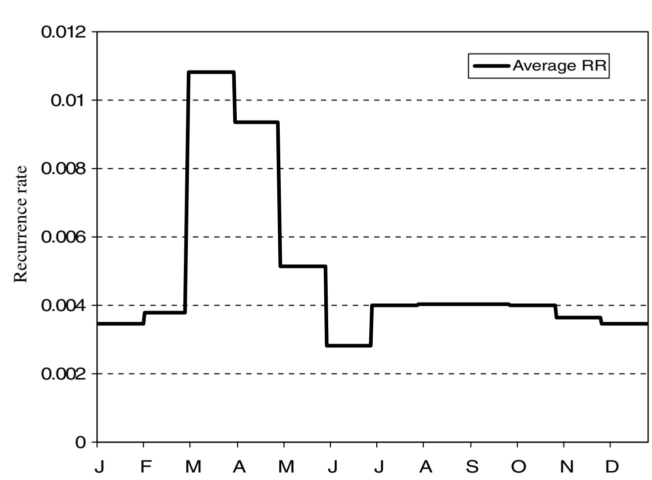

Fig. 11 Monthly average recurrence rate for water separator.

during a fraction T_n where $T_a + T_n = 1$. Then, the average recurrence rate should be equal to

$$\text{RR} = \lambda_a T_a + \lambda_n T_n \tag{5}$$

For the water separator under consideration the recurrence rate at adverse weather is $\lambda_a \approx 0.0084$ and $T_a = 3/12$. The recurrence rate at normal weather is $\lambda_n = 0.0033$ and $T_n = 9/12$. When inserted into Eq. (5), one obtains $\text{RR} = 0.0046$ which is very close to the recurrence rate obtained from the flight-hour based MCF analysis and exactly equal to the failure rate obtained from the Weibull analysis. However, neither flight-hour based MCF analysis nor parametric Weibull method can detect the variation of occurrences of water separator failures at certain periods of the year due to weather conditions. This hidden information which is revealed by applying the simple graphical technique is invaluable for an operator or MRO. First, it allows them to do better spare planning management, and prevent possible long aircraft turnaround times due to unavailability of the component in a period with a high recurrence rate. Second, it enables them to shape the maintenance schedule to best fit the particular environmental conditions. For example, the results obtained from this simple graphical analysis may indicate that the optimum maintenance policy for this component might be to use alternate inspection intervals (shorter intervals in spring and longer intervals in other seasons), rather than fixed intervals throughout the year. An MRO can use the same method of analysis to compare failures with other operators in its portfolio to see if the problem is common or specific to some operators and develop flexible, customized solutions that meet operators' specific requirements. The graphical analysis discussed above also provides any MRO with a powerful method of quantifying and justifying its solution to a customers' management in very easy, effective, and most revealing presentations. The information obtained is also very useful in planning field service team deployments for fast response. Manufacturers also benefit from the information for design improvements and producing customized components for the operators or MROs who suffer from the problem if the cost-benefit analysis justifies it.

2. *Heat Exchanger*

Heat exchangers require visual inspection and cleaning of primary and secondary heat exchangers. There are 19 reported failures for both of the heat exchangers. Figure 12 indicates cumulative failures of heat exchangers at each cooling pack and the resulting MCF. There is no misbehaving system from the point of heat exchanger failures. It is also seen that the MCF is changing almost linearly with flight hours; therefore, the failures seem to occur randomly with a nearly constant recurrence rate. MCF may be fitted very well ($R^2 = 0.9855$) with a straight line through the origin and the cumulative recurrence rate can be calculated as the slope of this straight line as $\text{RR} = 0.0006$. Mean time between failures then is estimated as 1667 h which is slightly lower than 2000 h which is the inspection interval recommended by the manufacturer. It is possible to make a more thorough analysis similar to the one which was carried out for the water separator to extract more information. The recurrence rate plot and $1/\text{MTBF}$ for the same component are shown in Fig. 13. The recurrence rate first decreases to 0.0005 at 1000 h. It remains fairly stable at this rate for about 1500 h and then becomes trendless.

3. *Air Cycle Machine*

The air cycle machine is a subsystem in the air cooling system. It consists of a compressor, a turbine, and an impeller fan connected by a common shaft which rotates at high speed. The air cycle machine is not replaced but is repaired when it fails. Thus, although it is a subunit similar to the water separator bag in the air cooling system, its failures cannot be modeled by parametric methods which use renewal theory. This may be confusing for an average practitioner who tries to analyze the failures. Using graphical method eliminates such confusion.

Each air cooling pack has an air cycle machine. For convenience, the machine in each pack is designated with the same number of the pack. There are 21 failures reported for this unit over six packs. Figure 14 indicates cumulative failures and MCF with confidence bounds for the air cycle machine against flight hours. It can be seen that the slope of the MCF is increasing with flight hours; therefore,

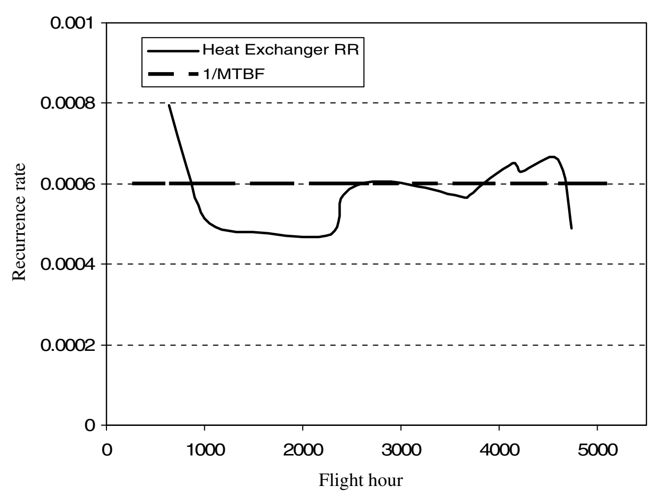

Fig. 13 Recurrence rate for heat exchanger.

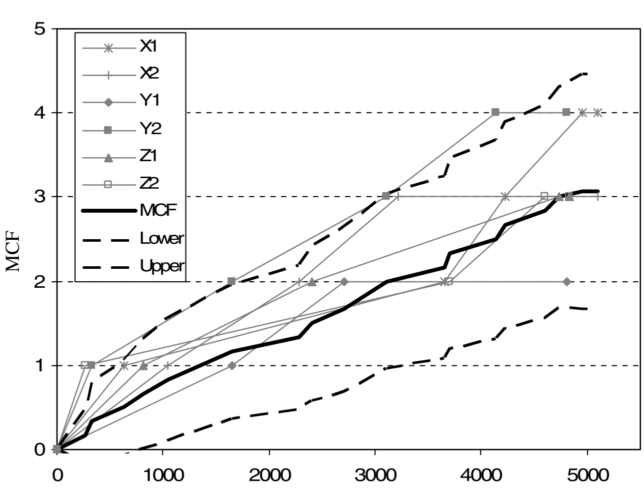

Fig. 12 Mean cumulative function for heat exchanger.

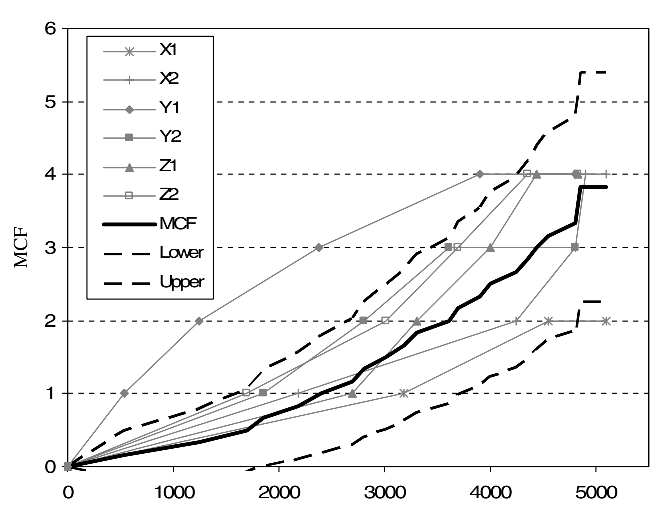

Fig. 14 Mean cumulative function for air cycle machine.

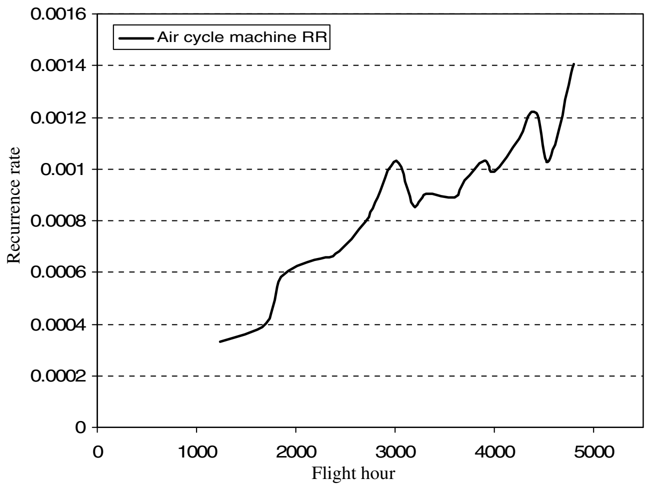

Fig. 15 Recurrence rate for air cycle machine.

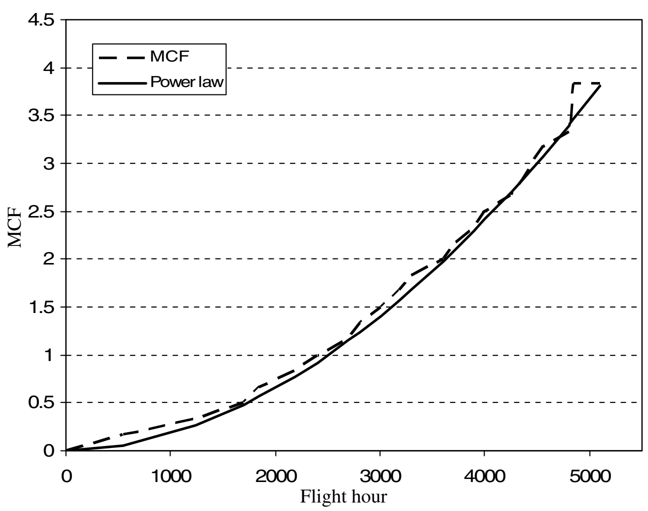

Fig. 16 Fitting power law model through air cycle machine mean cumulative function.

the rate of occurrence of the failures increases with age. In other words, the failure pattern seems to be dominated by wear-out failures for the air cycle machine. This usually points to problems such as aging, erosion, or imperfect repair. Figure 14 also indicates that the air cycle machine installed on system Y1 falls above the upper confidence bound. Visual interpretation of Fig. 14 indicates that system Y1, which has four failures, is in fact not the system with the highest number of air cycle machine failures during the observation period. Air cycle machines on systems X2, Z1, and Z2 have also failed 4 times; but system Y1 has experienced three failures in 2400 h. Therefore, the anomaly of the system Y1 may be attributed to clustering of failures. In fact, the shape of the cumulative curve suggests that the system Y1 is suffering from early failures. After the third failure, the system behaves within the confidence bound. The maintenance records indicate that the first three air cycle machine failures in system Y1 were due to a compressor discharge duct problem. In response to the first two failures, the duct was repaired. In the third failure, the duct was replaced. Because similar duct repairs have also been carried out on air cycle machines in other systems, imperfect repair cannot be considered as the cause of the anomaly in system Y1. Thus, it is very likely that the original compressor duct installed on the air cycle machine was already dead on arrival and it caused misbehavior of system Y1 until it was replaced. Figure 15 indicates the recurrence rate of the air cycle machine over flight hours. Although there are variations in recurrence rate, the general trend is upward. One can see that the rate of failures increases until 3000 h then falls. The rate remains fairly constant for about 800 h. Then it increases again until 5000 h with some fluctuations.

Although it was mentioned earlier that a parametric model such as NHPP fitting involves sophisticated procedures, it might be required for prediction and extrapolation purposes. In those situations, a power law model or other NHPP models can be used to fit the appropriate function through the nonparametric MCF. Figure 16 indicates fitting the power law model through MCF for the air cycle machine. The function used was $\mathrm{MCF} = a(\text{Flight hour})^b$, where a and b are constants determined from model fitting. The resulting function is

$$\mathrm{MCF} = 4 \times 10^{-7} t^{1.8823}$$

This enables the analyst to estimate the number of failures over a time window with a confidence interval. Further information on application of the method can be found in [6].

VI. Conclusions

The analysis of aircraft system failures does not have to be complicated. Graphical techniques presented in this paper provide a very powerful method for measuring and monitoring field failures of aircraft systems. The graphical techniques allow engineers to quickly identify failure trends, misbehaving systems, unusual behaviors, the effects of environmental conditions, maintenance practices, repair actions, and so on. The charts prepared by using the procedures discussed in this paper are easier to understand and far more revealing than the conventional methods proposed for the management and maintenance activities.

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