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Operational reliability analysis applied to a gas turbine based on three parameter Weibull distribution

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1. Introduction

The first objective in gas and oil project is to increase efficiency in the use of equipment, with down time reduced and their startup with the application of sophisticated methods of exploitation to increase the life service of the used equipment. This work presents the development of tools for decision support, based on operational reliability analysis of the exploited equipment in oil installations, for the determination of maintenance actions. These equipments are subject to degradation mechanisms due to the operating conditions and / or environment: wear, fatigue, aging and various physic-chemical changes [1-3]. Given to these resulting failures, it is sufficient to perform robust reliability methods. In this paper, is more protective to implement the Weibull distribution to optimize the running time of an exploited gas turbine, deciding to intervene just in time, in the oil installations. For contribute to the development and the analysis of reliability of this system and to improving maintenance strategy for future applications.

Nowadays, modern gas and oil installations are becoming more complex, at the same time, reliability, availability, and dependability have become very important and they are real challenges for businesses today. The reliability study appeared in order to improve the availability of its systems, from reliability models; these models can be static, such as fault trees, or behavioral, exploitable using analytical methods [4-7]. Several studies have been made in the literature to develop reliability methods, based on different information available to describe the behavior of systems. Moreover, the work developed in recent years by Osama Ashour et al, 2012 [8], Tung-Liang Chen, 2009 [9] Wenbin Dong et al, 2012 [10], Wenbin Dong et al, 2013 [11], have also invested in this area by developing a general methodological framework for modeling system reliability, to the implementation of its models in the planning of the maintenance strategy.

In deterministic approaches developed in several studies [1, 12-14], the reliability is the system resistance to sustained loads is assumed to be known and time-invariant, regardless of the type of system. In fact, this capacity may differ depending on the type of equipment, and for various reasons; changes in system properties, dimensional tolerances and other factors that affect the conduct of a component or a system composed of several components, error in the manufacturing process [15-17]. In addition, the operating conditions are not, they either perfectly determined, these two elements of uncertainty, load and capacity, make random the proper functioning of the system. This work deals with a qualitative and quantitative analysis of operational reliability for the safe operation of gas and oil installations. Through a number of historic features and equipment used in gas and oil industry, by the examination of a gas turbine in our experimental investigation. The developed model was validated for different situations, to help the operator in design and optimize the reliability of the gas turbine studied. The studied approach in this work was validated by experimental testes to confirm their effectiveness.

2. Industrial systems reliability

Reliability is the characteristic of a system expressed by the probability that perform the function for which it was designed, in given conditions for a given period [18, 19]. The lifetime of a industrial system is measured by the number of hours they actually worked, is a non-negative random variable, from which the act of degradation of the system can be determined. The equation (1) expresses the probability $P(t)$ that the lifetime T of the industrial system is comprised between t and $t+dt$.

$$f(t)dt = P(t \prec T \le t+dt), \tag{1}$$

with $f(t)$ is the probability density associated to the lifetimes. As for the distribution of lifetimes $F(t)$ and reliability function $R(t)$, they are related by the Eq. (2):

$$F(t) = P(T \le t) \text{ and } R(t) = P(T \succ t) \tag{2}$$

The failure rate $r(t)$ is the function to characterize the degradation law system. This is the conditional probability of failure per unit time of a system that survived until t. However, the law of degradation of an industrial system is completely defined by the knowledge of one of these four characteristics. For our application, we will use Weibull distribution, this law has the advantage of being very flexible and able to adjust to different experimental results [6, 20]. The reliability of a system expressed by Weibull is given by the following equation:

$$R(t) = e^{-\left(\frac{t-\gamma}{\eta}\right)\beta}, \tag{3}$$

with β is the shape parameter (unitless), η is the scale parameter (unit of time) and γ is the location parameter or origin (unit of time).

For repaired equipment is intended to be reused after refurbishment, the reliability or the failure rate is a basic feature less common but nonetheless indispensable. Indeed, the failure rate reflects the frequency of failures that is not the availability (and this frequency becomes constant). The reliability is not enough to define the efficiency of a system; we must measure the availability when the system is multi-component and repair. The Fig. 1, shows that availability can be improved by an increase in average uptime through reliability and a lower average time to repair for maintainability.

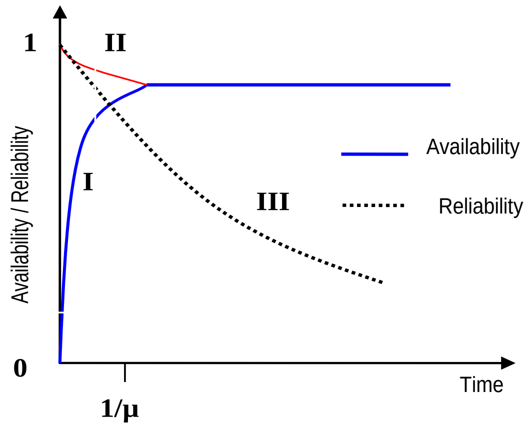

Fig. 1 Reliability of repairable systems

In the literature, there are several strategies to periodic replacement [3, 6, 14, 18], those age when substitutions are made to the failure and after units of time without failure and those with block-replacements at predetermined times**,** regardless of age and type the condition of the equipment**.** In these strategies**,** the average repair time decreases as the preventive actions generally better prepared and faster, just reduce the need for corrective actions.

3. Industrial application

In this work, we consider a gas turbine type GE MS3002 installed in Hassi R'Mel, Algeria gas plant, shown in Figs. 2 and 3, used in the gas pipeline network activities to transport the gas along Hassi R'Mel pipeline. The objective of this work is to make an analysis of operational reliability, based on data feedback, to allow a better exploitation of the examined gas turbine. The entire turbine con-

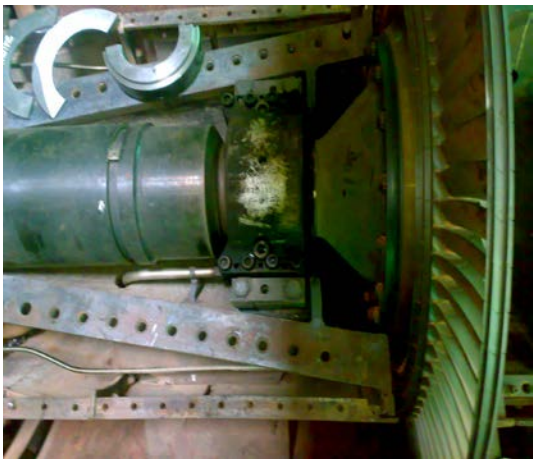

Fig. 2 Rotor failure in examined gas turbine

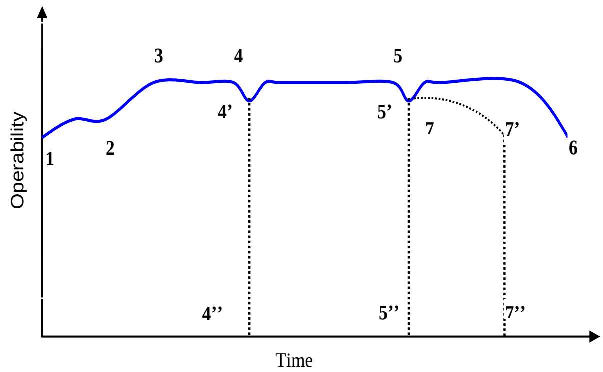

Fig. 3 Examined gas turbine in revision with the change in the functionality

sists of three main components: the axial compressor, the combustor and turbine. This system is operated at about 50% of their maximum speed to maintain the compression cycle. The energy cost becomes very high when operating the compressor at idle or at low load.

3.1. Application results

The examined gas turbine at the Hassi R'Mel, Algeria are MS 5002 model, they are used to drive multi-storey centrifugal compressors, where the data has been collected from the history of the studied gas turbine is given in Table 1.

From the times between failures (TBF), the general expression to calculate the average uptime MTBF is given by the flowing relation:

$$MTBF = \frac{\sum_{1}^{40} TBF}{\eta} = 2084 \text{ h.}$$

According to the Sturges rule given in [12], to grouping in the order of magnitude of the amount of data

Table 1

History data of the studied gas turbine MS 5002 model

N°	Date	TBF	N°	Date	TBF	N°	Date	TBF	N°	Date	TBF
1	12-03-97	768	11	12-12-98	648	21	28-06-2001	3024	31	12-07-2004	2808
2	12-05-97	1440	12	24-03-99	2232	22	16-02-2002	3912	32	24-09-2004	1704
3	28-05-97	432	13	16-05-99	1344	23	15-03-2002	2880	33	15-12-2004	1680
4	22-11-97	4128	14	18-09-99	2808	24	15-08-2002	2928	34	08-03-2005	2040
5	22-12-97	1440	15	08-12-99	1992	25	16-04-2003	3936	35	17-05-2005	1656
6	12-04-98	1920	16	06-04-2000	2880	26	26-05-2003	1704	36	27-08-2005	2160
7	11-05-98	696	17	18-07-2000	2472	27	25-06-2003	672	37	22-10-2005	1296
8	12-06-98	720	18	18-10-2000	2352	28	27-11-2003	2952	38	29-12-2005	1656
9	22-06-98	216	19	13-11-2000	3452	29	08-12-2003	1704	39	28-03-2006	1512
10	19-11-98	3648	20	16-12-2000	1224	30	16-03-2004	2280	40	22-06-2006	3672

that is important to determine the number of classes. This rule varies the integer r classes or intervals to be based on the number n of data, we can determine the number of classes as follows:

$$r = 1 + 3.3 log_{10} \sum_{i=1}^{i=40} n_i \ .$$

Knowing that $\sum_{i=1}^{i=40} ni = 40 \Rightarrow r = 6.28$.

We take $r = 7$ class and the interval time for each class is as follows:

$$\Delta T = \frac{TBF_{max}}{r} = 590 \text{ h} \quad \Rightarrow \ \Delta T = 590 \text{ h}.$$

Following these intervals time for each class for 40 items, easily we obtain the distribution of failures per class in the Table 2.

Table 2

Distribution of failures per class

Interval	Failure number	Class failures
0 - 590	2	0.05
590 - 1180	5	0.125
1180 - 1770	12	0.3
1770 - 2360	7	0.175
2360 - 2950	6	0.15
2950 - 3540	3	0.075
3540 - 4128	5	0.125

The next step is to construct a histogram of failures from the distribution of failure $\bar{P}(t)$ and from the probability of non failure $P(t)$ and thus deduce that the law follows:

$$\bar{P}(t) = 1 - P(t) = \frac{n_i}{N}, \tag{4}$$

with n_i is the number of failures until time t_i and N is the number of blackouts.

For the probability of failure and the non failure probability was given by the Table 3.

Table 3

Probability of failure

t_i	$\bar{P}_i(t_i)$	$P_i(t_i)$
t_0	0	1
t_1	0.05	0.95
t_2	0.125	0.875
t_3	0.475	0.525
t_4	0.650	0.350
t_5	0.800	0.200
t_6	0.875	0.125
t_7	1	0

To determine the failure rate in the examined gas turbine, we used the follows equation:

$$\lambda_i = \frac{n_i}{Nt \, \Delta t}, \tag{5}$$

with n_i is the number of failures during Δt_s and N_t is the number of survirants early time slot t_i, ie. it is the total number of failures decreased the number of failures to previous time $(t-1)$.

Using the Eq. (2) and the history of the examined gas turbine in Δt time interval observed, we obtained the failure rate as Table 4.

Table 4

Failure rate

t_i	$\lambda_i \ (1/h)$
t_0	$8.474 \cdot 10^{-5}$
t_1	$2.230 \cdot 10^{-4}$
t_2	$52.568 \cdot 10^{-5}$
t_3	$7.260 \cdot 10^{-4}$
t_4	$7.260 \cdot 10^{-4}$
t_5	$8.471 \cdot 10^{-4}$
t_6	$6.355 \cdot 10^{-4}$
t_7	$16.690 \cdot 10^{-4}$

In this case the fit test is request, the failure rate results have tested using the Kolmogorov-Smirnov fit test, it consists in comparing the absolute error given by the difference between the actual and the theoretical static function, with $\Delta_{\eta,\infty}$ reference selected, depending on the number total of failures η, knowing that the latter is the samples size of η with α risk of error. Assuming a risk of error $\alpha = 0.05$ with the adequacy condition $\Delta D_{max} \prec D_{\eta,\alpha}$ and ΔD_{max} the absolute error between the actual and the theoretical function, we used the fit test as follows:

$$\sigma = \sqrt{\sum_{i=1}^{7} U_i t_i{}^2 - F^2}\ , \qquad (6)$$

with the function is given by $\frac{i}{n+1}$, which i is the order of t_i and n is the total number, in the examined system is 40.

$$D_{n,\alpha} = \frac{1.36}{\sqrt{n}} = \frac{1.36}{\sqrt{n}} \Rightarrow D_{n\alpha} = 0.21.$$

The set function is given by:

$$F(t) = \frac{1}{\sigma\sqrt{2\pi}} \int_0^{t_i} e^{-\left(\frac{t_i - F_1}{2\sigma^2}\right)^2} dt\ . \qquad (7)$$

Effectively change the variable $U_i = \frac{t_i - \bar{t}}{\sigma}$, by taking into account that $\sum(-x) = 1 - \varphi(x)$, and we calculate the mathematical expectation $\bar{T} = \sum_{i=1}^{7} U_i t_i$ and standard deviation $\sigma^2 = \sum_{i=1}^{7} U_i t_i{}^2 - \bar{T}$, the results are regrouped in the following Table 5.

Table 5

Results of the standard deviation

Δt_i	$t_i(h)$	N_i	$U_i = \frac{n_i}{N}$	$U_i t_i$	$U_i t_i^2$
0-590	295	2	0.050	13.250	4351.250
590-1180	885	5	0.125	110.625	97903.125
1180-1770	1475	12	0.300	442.500	652687.500
1770-2360	2065	7	0.175	361.375	746239.000
2360-2950	2655	6	0.150	398.250	1057353.750
2950-3540	3245	3	0.075	243.375	789751.875
3540-4128	3835	5	0.125	479.375	1838403.125
Total	-	40	-	2048.750	586690.000

One conclusion:

$$\bar{T} = \sum_{i=1}^{7} U_i t_i \quad = 2048.75 \text{ h},$$

$$\bar{T} = MTBF = 2048.75 \text{ h},$$

$$\bar{T} = 3 \text{ month}$$

or

$$\sigma = \sqrt{\sum_{i=1}^{7} U_i t_i{}^2 - \bar{T}^2} = 994.64 \Rightarrow \sigma = 994.64$$

Table 6

Results of the adequacy condition tests

t_i	$U_i = \frac{t_i t}{\sigma}$	$F_{th}(t)$	F_i	ΔD	$D_{\eta,x}$
295	-1.76	0.04	0.05	0.010	0.21
885	-1.170	0.121	0.125	0.004	0.21
1475	-0.58	0.281	0.475	0.194	0.21
2065	0.02	0.5080	0.650	0.142	0.21
2655	0.61	0.729	0.800	0.071	0.21
3245	1.20	0.8849	0.875	0.009	0.21
3835	1.79	0.9633	1	0.036	0.21

According to the results Table 6, we see that $\Delta D_{max} = 0.194$, so after the fit test that should be $\Delta D_{max} = 0.1231 \prec D_{\eta,x} = 0.210$. Therefore, it is confirmed that Weibull distribution is appropriate for the distribution of failures in the studied gas turbine GE MS5002, using the median ranks to determine the Weibull parameters of the law for the MTBF and to determine the associated reliability of the examined gas turbine.

The Figs. 4, 5 and 6 showed the results of Weibull distribution with tow parameters for the sample times to failure, using the historical failure data of the investigated gas turbine. In Fig. 4 the evolution of the reliability function of the examined gas turbine GE MS5002 using Weibull with two parameters is shown, in Fig. 5 the cumulative failure using Weibull distribution with tow parameters of the examined system is presented, the results are given by two different curves in one graph, the first curve in continuous line represent the fitting tests using compared data by Sturge's rule in the second curve shown by discontinuous line. And the Fig. 6 showed the hazard function using Weibull distribution with tow parameters, this hazard function given the force of mortality in the examined gas turbine.

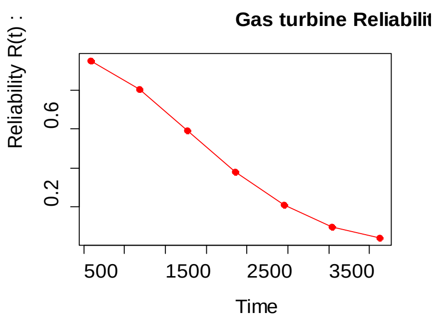

Fig. 4 Reliability function using Weibull distribution with tow parameters of the examined gas turbine

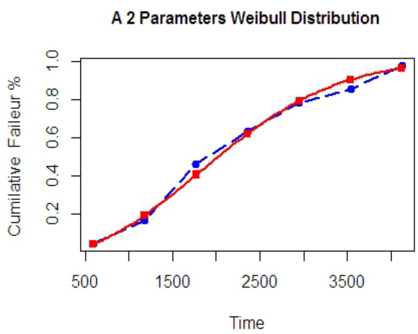

Fig. 5 Cumulative failure using Weibull distribution with tow parameters of the examined gas turbine

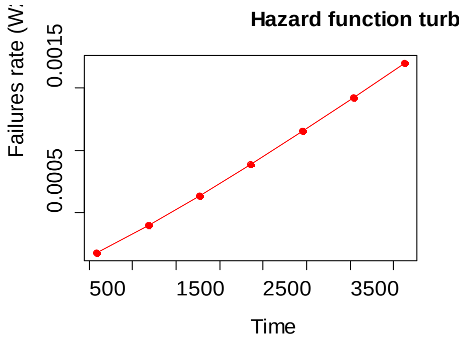

Fig. 6 Hazard function using Weibull distribution with tow parameters of the examined gas turbine

The Figs. 7, 8 and 9 showed the results of Weibull distribution with three parameters for the sample times to failure, using the historical failure data of the investigated gas turbine. The Fig. 7 present the evolution of the reliability function of the examined gas turbine GE MS5002 using Weibull distribution with three parameters, in Figure 8 the cumulative failure using Weibull distribution with three parameters of the examined system is shown, the results are given by two different curves in one graph, the first

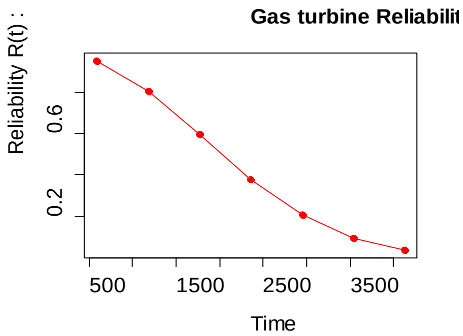

Fig. 7 Reliability function using Weibull distribution with three parameters of the examined gas turbine

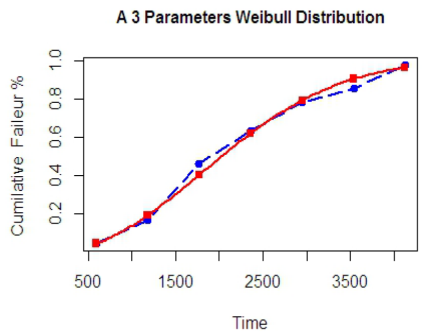

Fig. 8 Cumulative failure using Weibull distribution with three parameters of the examined gas turbine

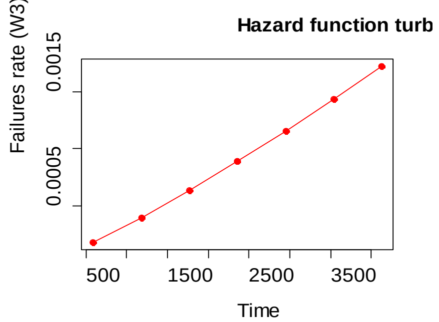

Fig. 9 Hazard function using Weibull distribution with three parameters of the examined gas turbine

curve in continuous line represent the fitting tests using compared data by Sturge's rule in the second curve shown by discontinuous line. And the Fig. 9 showed the hazard function using Weibull distribution with three parameters, this function given the survivor function of the examined gas turbine

From the obtained results, we confirm that the reliability of the studied gas turbine for t = 2160 h, corresponding to the length of effective market for a quarter (3 months). The gas turbine GE MS5002, operate without failure for 3 months with a probability of 32.1%.

4. Conclusion

The developed model in this work, for operational reliability analysis applied to a gas turbine based on Weibull distribution with three parameters, was validated for different situations. The risk of the reliability error between the actual and the theoretical function of the examined system is equal to $\alpha = 0.05$ is a very acceptable value. Also, the adequacy condition is equal to $\Delta D_{max} = 0.194$ and after the fitting tests become $\Delta D_{max} = 0.210$, this confirms that Weibull distribution is appropriate for the distribution of failures in the studied gas turbine GE MS5002 in order to help the operator in design and optimize the reliability of the gas turbine. Indeed, the studied approach in this work, based on experimental investigation using Weibull distribution was validated by real tests to confirm their effectiveness. This work is carried out a proper analysis of operational reliability, based on data feedback to allow a better exploitation of the turbine. The proposed qualitative and quantitative analysis using operational reliability for the safe operation in oil and gas installations, using Weibull distribution with tow and three parameters give a good optimization of the operation of this system and meet the production in the examined installation. The used operational reliability found good results from a maintenance policy, which derive a planning revise (partial, full) and maintenance during this planning time.

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OPERATIONAL RELIABILITY ANALYSIS APPLIED TO A GAS TURBINE BASED ON THREE PARAMETER WEIBULL DISTRIBUTION

S u m m a r y

The paper focuses on the problem of reliability analysis in industrial equipment, to give the engineer to get better maintenance plans, based on right decision formulate by reliability design. In this work, the gas turbine reliability is modelled by the Weibull distribution in different exploitation time, to optimize the operation and to meet the production. Experimental tests and results presented in this paper confirm the effectiveness of the proposed approach.

Keywords: Reliability analysis, operational reliability, Weibull distribution, availability, gas turbine.

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