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Modelling of Non-Monotonic Hazard Function for the Early Production Life of Oil and Gas Plants

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***Abstract* – Common reliability models rely usually on simple assumptions as to manage constant failure rates especially when electronic components are treated in the reliability block diagram. Nevertheless, more realistic modeling imply to deal with Weibull based hazard functions or even with more complex models. For oil and gas plants, and repairable systems in general, actually, it may happen to deal with non-linear behavior of the failure intensity function. Multiple slope changes may occur due to long observation time and to restoration activities affecting the overall system performance and failure rate shape over time. Commissioning phase is of particular interest for electro-mechanical complex systems because, depending on the plant extension and design, it can influence the hazard function shape and therefore its model. In this paper the authors will try to show how experimental failure rate information can be modeled by means of different hazard functions.**

I. INTRODUCTION

Common hazard function models rely on traditional assumption of exponential probability density function especially whenever dealing with electronic components so that the failure rate can be assumed as constant over time. For mechanical components, usually, Weibull probability density function is assumed so that the bath-tube curve modeling both infant mortality, constant failure rates and wear out conditions can be modeled depending on the shape parameters assumed time by time by the needed framework conditions as described in [1]. Some authors have tried to start dynamic modeling of the failure rates [2],[3] in order to take into account a sort of parameters variability over time which is connected not to the component itself, but to the specific application.

Nevertheless such approaches are devoted to take into account the changes of the operating conditions over time to implement reliability block diagrams which can, in principle, describe situations where the failure rate can change due to operating condition variations. Actually even if some traditional and well known data base (as the MIL-HDBK-217) hypothesis are exploited, results usually maybe of two types [4-20]. There are worst cases with respect to the actual system behavior over time due to over estimates of the used failure rates and there are optimistic forecasts connected to wrong assumptions on stress factors or environmental conditions stability. These estimates are the basis of any reliability and availability prediction based on homogeneous Markov modeling, on fault tree analysis, or any other classical reliability analysis tool [7-10],[14-20].

Out of this variability some researchers started to design more complex probability density functions to be exploited to model non-monotonic hazard functions in a closed form [2]. Nevertheless the proposed solutions, even if valid, can be applied only for cases where infant mortality is followed by wear-out conditions.

In oil and gas plants the overall hazard estimate is strictly linked to the operating phases of the plant itself. Therefore a more complete formulation to represent a wider (and more comprehensive) plant life parameters variation over time is needed.

II. PROBLEM FORMULATION

Usually the setup of huge oil and gas plants or gas turbines for power generation purposes requires extended tuning time and long commission phases. However improved performance productivity targets push plant operational organization to shrink commissioning times. Even if, theoretical reliability studies are performed assuming a standard Weibull probability density functions for each mechanical component and exponential ones for the electronics the final outcome may result far from the actual one due to such changes in system setup.

An example of such actual behavior is shown in Figure 1 where the failure intensity (the same effect can be seen in the hazard function) graph for the first 2500 observed hours is represented for eight homogeneous repairable plants which have been monitored for a total amount of 200kh.

Out of Figure 1 it is evident that the traditional proposed approach based on single Weibull structure does not fit the field data as well as traditional non homogeneous Poisson processes (NHPP) exploited for repairable systems. The reasons why the different behavior is observed can be endorsed to several causes.

Nevertheless, the major contribution, for this specific applications, is given by the long commissioning phases linked to the plant time constraints.

The represented points take into account a collection of several repairable systems where multiple system failures have been managed as new failures of an identical system embedding for each item suspensions as censored data too. Failures have been gathered according to time bins. Data of interest for fitting problems are shown only.

Due to the confidential nature of the data, real figures were modified. The shape of the failure intensity function versus time was anyhow preserved for the benefit of the present study. Therefore absolute values of data are not to be considered for any reference.

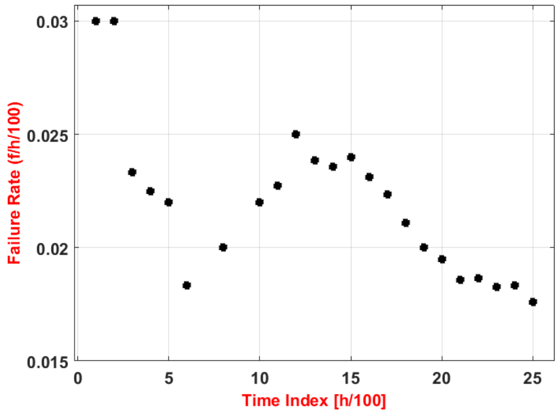

Fig. 1. Failure rate of eight Oil and Gas plants in the first 2500 observation hours.

Actually every brand new plant has to follow strict time schedule and issues occurring during commission phases might be solved without completely addressing the root causes. This may expose to the possible re-occurrence of the issues. Usually the tuning phase should be slow and problem solution may be difficult since new issue can come over with time and plant adjustment. Productivity rush has shrunk operation times enormously. Moreover, as the plant installation and commissioning phases progress, a rotation of resources may take place. The faster the rotation of personnel is, the higher the probability that the knowledge transfer from the installation to the operation team as well as the spread of the lessons learnt will be incomplete.

The lack of operational teams information transfer increase the risk to undergo to partially solved problems during plant setup, jeopardizing in this way all the efforts previously done to address solutions. All this contribution together can explain the unexpected behavior of the failure intensity function, which shows a decreasing trend in the frequency of issues during the first period of operation, followed by a period with increasing number of discovered issues and finally by a gradual reduction of the failure rate. This does not fit very well the traditional Weibull based curve.

III. HAZARD FUNCTION MODELING

In the present work therefore the authors propose an alternative model to describe the hazard function in order to follow the failure intensity by means of a combination of multiple Weibull based probability density functions. More in general such behavior can be approximated with a polynomial n-order function once the shape has been determined by experimental failures and suspensions. Nevertheless such solution is not of practical use since additional constraints have to be added to exploit the polynomial expression in the reliability context. The authors selected a Weibull based reliability function as per (1) taking into account that different failure modes can take place simultaneously.

$$R(t) = e^{-\left[\left(\frac{t}{\eta_1}\right)^{\beta_1} + \left(\frac{t}{\eta_2}\right)^{\beta_2} - \left(\frac{t}{\eta_3}\right)^{\beta_3}\right]} \tag{1}$$

It is then possible to derive by means of (2) the correspondent probability density function represented in (3).

$$f(t) = -\frac{dR(t)}{dt} \tag{2}$$

$$\begin{aligned} f(t) = {} & \frac{\beta_1}{\eta_1}\left(\frac{t}{\eta_1}\right)^{\beta_1 - 1} e^{-\left[\left(\frac{t}{\eta_1}\right)^{\beta_1} + \left(\frac{t}{\eta_2}\right)^{\beta_2} - \left(\frac{t}{\eta_3}\right)^{\beta_3}\right]} + \\ & + \frac{\beta_2}{\eta_2}\left(\frac{t}{\eta_2}\right)^{\beta_2 - 1} e^{-\left[\left(\frac{t}{\eta_1}\right)^{\beta_1} + \left(\frac{t}{\eta_2}\right)^{\beta_2} - \left(\frac{t}{\eta_3}\right)^{\beta_3}\right]} + \\ & - \frac{\beta_3}{\eta_3}\left(\frac{t}{\eta_3}\right)^{\beta_3 - 1} e^{-\left[\left(\frac{t}{\eta_1}\right)^{\beta_1} + \left(\frac{t}{\eta_2}\right)^{\beta_2} - \left(\frac{t}{\eta_3}\right)^{\beta_3}\right]} \end{aligned} \tag{3}$$

By knowing that the hazard function can be expressed by (4) and by exploiting expressions (3) and (1) it is possible to obtain (5).

$$h(t) = \frac{f(t)}{R(t)} \tag{4}$$

$$h(t) = \frac{\beta_1}{\eta_1}\left(\frac{t}{\eta_1}\right)^{\beta_1 - 1} + \frac{\beta_2}{\eta_2}\left(\frac{t}{\eta_2}\right)^{\beta_2 - 1} - \frac{\beta_3}{\eta_3}\left(\frac{t}{\eta_3}\right)^{\beta_3 - 1} \tag{5}$$

Equation (5) is the closed form of the hazard function which can be used to obtain a fitting curve for data as the one represented in Figure (1), once proper usability constraints have been added.

$$R(t) \approx 1 - \left(\left(\frac{t}{\eta_1}\right)^{\beta_1} + \left(\frac{t}{\eta_2}\right)^{\beta_2} - \left(\frac{t}{\eta_3}\right)^{\beta_3}\right) \tag{6}$$

The problem reduces to identify the six function parameters knowing that the failure intensity function is not constant. In fact it should model a decreasing trend during the commissioning phase, followed by an increasing trend at the beginning of the production phase and eventually a further decreasing trend during the mature production phase.. It is therefore possible to approximate (1) with (6). Passages from (7) to (10) allows to reduce further expression to the point when the constraints imposed by (11) have to be added.

$$\left(\frac{t}{\eta_1}\right)^{\beta_1} + \left(\frac{t}{\eta_2}\right)^{\beta_2} < 1 + \left(\frac{t}{\eta_3}\right)^{\beta_3} \tag{7}$$

$$t^{\beta_1} + \frac{\eta_1{}^{\beta_1}}{\eta_2{}^{\beta_2}} t^{\beta_2} < \eta_1{}^{\beta_1} + \frac{\eta_1{}^{\beta_1}}{\eta_3{}^{\beta_3}} t^{\beta_3} \quad (8)$$

$$1 + \frac{\eta_1{}^{\beta_1}}{\eta_2{}^{\beta_2}} t^{\beta_2-\beta_1} < \frac{\eta_1{}^{\beta_1}}{t^{\beta_1}} + \frac{\eta_1{}^{\beta_1}}{\eta_3{}^{\beta_3}} t^{\beta_3-\beta_1} \quad (9)$$

$$\frac{1}{t^{\beta_2-\beta_1}} + \frac{\eta_1{}^{\beta_1}}{\eta_2{}^{\beta_2}} < \frac{\eta_1{}^{\beta_1}}{t^{\beta_2}} + \frac{\eta_1{}^{\beta_1}}{\eta_3{}^{\beta_3}} t^{\beta_3-\beta_2} \quad (10)$$

The following conditions expressed in (11) should be set in order to identify specific curve families:

$$\begin{cases} 0 < \eta_1 < \eta_2 < \eta_3 \\ 0 < \beta_1 < 1 \\ \beta_1 < \beta_2 \\ 0 < \beta_3 \end{cases} \quad (11)$$

In this paper we are looking to model specific failure intensity behavior as the one shown in Figure 1. Additionally, the first constraint in (11) is assumed due to the fact that characteristic life η is chosen to model infant mortality at the beginning of a product life usually [2-20].
Exploiting (11) is possible to derive (12) and express an additional condition on the final characteristic life (13).

$$2 < \frac{\eta_1{}^{\beta_1}}{t^{\beta_2}} + \frac{\eta_1{}^{\beta_1}}{\eta_3{}^{\beta_3}} t^{\beta_3-\beta_2} \quad (12)$$

$$\eta_3 < \sqrt[\beta_3]{\frac{\eta_1{}^{\beta_1} t^{\beta_3}}{2t^{\beta_2} - \eta_1{}^{\beta_1}}} \quad (13)$$

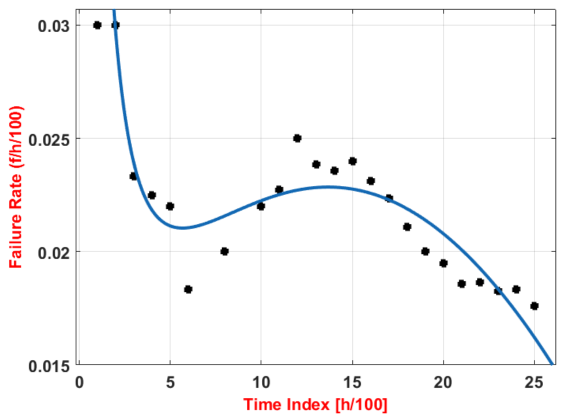

Fig. 2. Proposed failure rate structure fitting on experimental data of Figure 1 .

In Figure 2 a curve fitted with the conditions in (11) and (13) showing good approximation of the hazard function. Table I contains the identified parameters. Of course the adherence of the curve to the points is limited by the fixed order of the curve.

Equation (1) Weibull parameters	
β_1	0.04307
β_2	2.246
β_3	2.345
η_1[h/100]	0.07406
η_2[h/100]	12.02
η_3[h/100]	12.79

Table 1. Identified Parameters of the proposed model in equation (1).

Supposing to exploit these mathematical outcomes to model and ideal non-repairable component for simulation purposes, it is possible as shown in Figure 3 its correspondent reliability behavior. Of course this piece does not exist in practice and its behavior is assumed for non-repairable items.

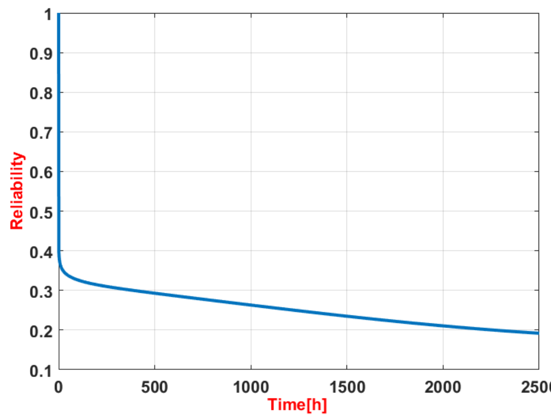

Fig. 3. Reliability behaviour over time of equation (1) with the parameter of Table I.

IV. CONCLUSIONS

In this paper the authors tried to provide a suitable model to describe the failure intensity function of complex oil and gas systems, especially during the commissioning and first period of production.
Specific logistic aspects, such as a rotation of personnel in the plants or a shortened commissioning period may lead to an unsteady situation, where the failure rate or hazard function may be modelled with difficulty.
Under this standpoint the authors propose a multi parameter Weibull based function to take into account different hazard function slopes.

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