ROCOF usage for Better than New Maintenance

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For the main part of industrial applications, systems are maintained in operational conditions and the classical reliability metric as the failure rate cannot be used. In fact, the corresponding reliability metric depends on the maintenance types such as the “As Bad As Old”, the “As Good As New” or other types of maintenance that will be not addressed here.
Another type usually occurs due to premature component wear-out, the “Better Than New” or BTN Maintenance. In this presentation, we first remind about the renewal process theory and especially the “Rate of Occurrence of Failures” (ROCOF) notions and their main properties. We explain how it is adapted to the BTN maintenance. Furthermore, for costing issues optimization, components can be replaced for any failure of the system and not only for their specific root cause. We present how to model the ROCOF in such a type of maintenance.
Finally, we propose an example coming from the aircraft industry to illustrate a theory that any reliability engineer should use one day.

Keywords: Operational Reliability, Maintenance, ROCOF, Optimization

1 Introduction

For life-limited components, maintenance strategies must be used to fulfill reliability, safety or availability objectives. Preventive maintenance was commonly used in the past but is not affordable anymore, especially for electronic components because of increasing availability requirements.

Life-limited components are mostly designed to move wear-out failure mechanisms far away the normal product service life, so that the wear-out failures are never met in the field. For instance, some electrolytic capacitors are often needed in order to mask micro-cuts possibly occurring in aircraft communication networks. Depending on the output power of the primary DC/DC converter on the needed transparency time, some capacitors in parallel are needed. However, their capacitance decreases with time and the time transparency will not be sufficient, leading to a soft failure of the product. Therefore some capacitors are added in parallel to avoid this type of failure.

Unfortunately, in some cases premature wear-out cannot be anticipated by design due to some weakness of design, mavericks lots during the component or product manufacturing, etc.
Classical maintenance, as perfect maintenance or As Good As New (AGAN) maintenance, strategies are usually performed for classical wear-out failure mechanisms. In the case of premature wear-out, this type of maintenance and the corresponding theory cannot be applied because the failed component is replaced by a new and healthy one that cannot have any premature wear-out behavior anymore because the design is modified, or the component or product manufacturing is corrected, or any other similar reason.

2 Theoretical background

2.1 Renewal process theory

If times to repair can be neglected, the renewal process theory can be used to model AGAN maintenance type. As the failure intensity is random, the notion of Rate Of OCcurrence Of Failures (Rocof) has been developed.
It is defined by:

$$Rocof(t) = \frac{d}{dt} E[N(t)] \tag{1}$$

where N(t) is the number of failures at time “t”

E is the expected value

It can be demonstrated [REF 01] that the Rocof can be written as a function of the probability density function of the underlying failure mechanism, as follows:

$$Rocof(t) = \sum_{i=1}^{+\infty} f^{<i>}(t) \quad (2)$$

where f(t) is the probability density function

$^{<k>}$ is the k-fold convolution product

Equation (2) can be rewritten as follows:

$$Rocof(t) = f(t) + f(t) * f(t) + \ldots + f(t) * f(t) * \ldots * f(t) + \ldots \quad (3)$$

where * is the convolution product operator

Again from the renewal process theory, it can be demonstrated [REF 01] that the Rocof has an asymptotic value when time tends to infinity. The following result is obtained:

$$\lim_{t \to +\infty} Rocof(t) = \frac{1}{MTTF} \quad (4)$$

If we want to estimate the mean number of failures at time "t", equations (1) and (2) lead to:

$$E[N(t)] = \int_0^t \sum_{i=1}^{+\infty} f^{<i>}(u).du = \sum_{i=1}^{+\infty} F^{<i>}(t) \quad (5)$$

where F(t) is the cumulative probability function

2.2 Rocof for wear-out failure mechanisms

In most of the cases, the Rocof(t) has no close form solutions. Only the exponential, the Normal and the Erlang distributions have analytic solutions. Albeit the Weibull distribution is a better model for wear-out failure mechanisms, in case of determining the shape parameter in a specific range of values, the Normal distribution can be used.

As the Rocof for Weibull distribution has no closed form, numerical convolution must be used. The next figure illustrates the Rocof behavior for a Normal distribution with Mean = 50 and Standard Deviation = 10:

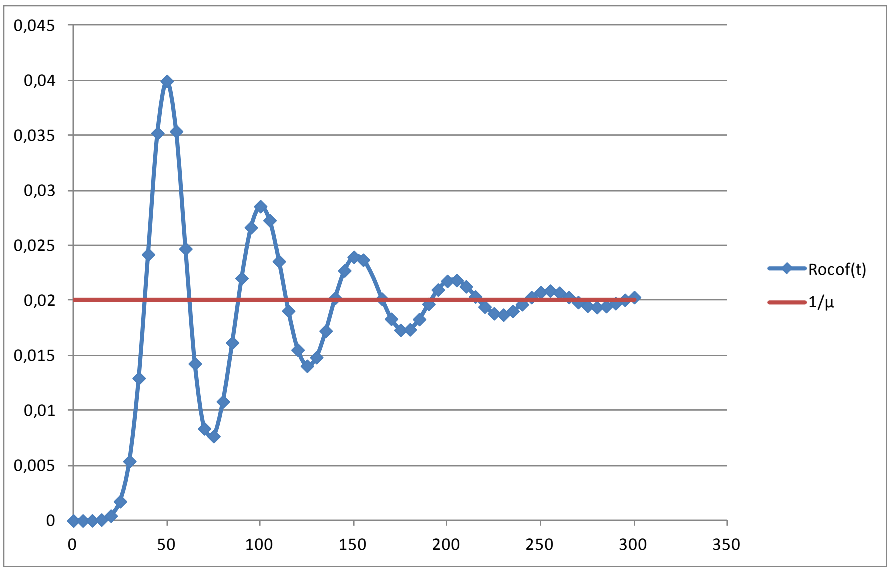

Figure 1

The corresponding mean number of failures is given by:

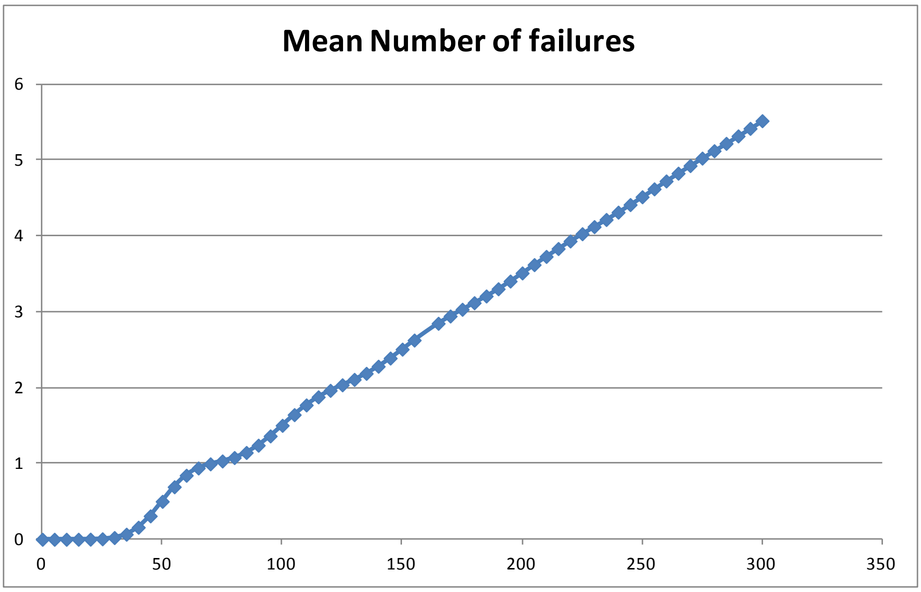

Figure 2

3 Maintenance strategies

"Design For Reliability" or DFR is a methodology that is used by engineers during the product design phase., Though the efficiency of this method, premature wear-out failure mechanisms can occur in the field due to design weakness, mavericks lots of, manufacturing defaults, ….

These premature wear-out mechanisms raise 2 important questions:

- Are the reliability, safety and maintenance objectives always fulfilled?
- What is the right strategy to address the previous question?

In case of premature wear-out, 2 solutions are possible:

- Replace the failed component by a new one (AGAN maintenance)
- Replace the failed component by a better one (BTN maintenance)

An alternate solution is to replace the component by a better one whatever the failure is; here we talk about Optimized Better Than New (OBTN) maintenance.

3.1 AGAN maintenance

For premature wear-out failure mechanisms, the Rocof is defined in paragraph 2.2. For simplification purpose, the asymptotic value is commonly taken into account. The total Rocof is the sum of the catalectic (exponential) and the wear-out (Weibull) Rocof and is given by:

$$Rocof(t) = \lambda_{catalectic} + \frac{1}{\eta.\Gamma\left(1+\frac{1}{\beta}\right)} \quad (6)$$

Where
- η is the scale parameter of the Weibull distribution
- β is the scale parameter of the Weibull distribution
- Γ is the Gamma function

Note that the MTTF of the Weibull distribution is not very sensitive to the shape parameter.

3.2 BTN maintenance

The BTN maintenance consists in replacing the failed component by a new one without any premature failure mechanism. It means that, after the weak component has failed with a premature failure mechanism, the component is replaced by a new component which has only catalectic failure mechanism.

The corresponding Rocof is so given by :

$$Rocof(t) = f_w(t) + f_w(t) * f_c(t) + \ldots + f_w(t) * f_c(t) * \ldots * f_c(t) + \ldots \quad (7)$$

Where
- $f_w(t)$ is the premature wear-out probability density function
- $f_c(t)$ is the catalectic probability density function

Equation (7) can be rewritten as follows :

$$Rocof(t) = \sum_{i=1}^{+\infty} \left[f_w(t) * f_c^{<i-1>}(t) \right] \quad (8)$$

3.3 OBTN maintenance

The OBTN maintenance consists in replacing the component by a new one without premature failure mechanism whatever the failure of the product is. In fact, competitive failure mechanisms occur at product level. The corresponding product probability density function $f_p(t)$ is then given by:

$$f_p(t) = f_e(t).R_w(t) + f_w(t).R_e(t) \quad (9)$$

Where
- $f_w(t)$ is the premature wear-out probability density function
- $f_e(t)$ is the probability density function of the other component of the product

In case of exponential and Weibull distributions, equation (9) can be written:

$$f_p(t) = \exp\left(-\lambda.t - \left(\frac{t}{\eta}\right)^{\beta} \right).\left(\lambda + \left(\frac{\beta}{\eta}\right).\left(\frac{t}{\eta}\right)^{\beta-1} \right) \quad (10)$$

From equations (8) and (10), the corresponding Rocof is obtained:

$$Rocof(t) = \sum_{i=1}^{+\infty} \left[f_p(t) * f_c^{<i-1>}(t) \right] \quad (11)$$

4 Industrial example

In this paragraph, the example of an electronic product is presented.

4.1 Premature wear-out estimation

After a few months operating, several failures were recorded on a polarized tantalum capacitor. From FIDES methodology [REF 02], the catalectic field Rocof was estimated at 54 Fits, meaning that none or 1 failure would normally be observed during this period of time.

After inspecting failed capacitors, it has been observed that each of those had a wrong polarity. Contrarily to manufacturer's datasheet [REF 03], where the capacitor should fail rapidly, it is actually not the case and a leakage current was observed on the capacitor of which amplitude is age-dependent. However, this leakage current is sufficient to lead to a product dysfunction.

Data from the field lead to the following Weibull parameter estimation and Weibull plot

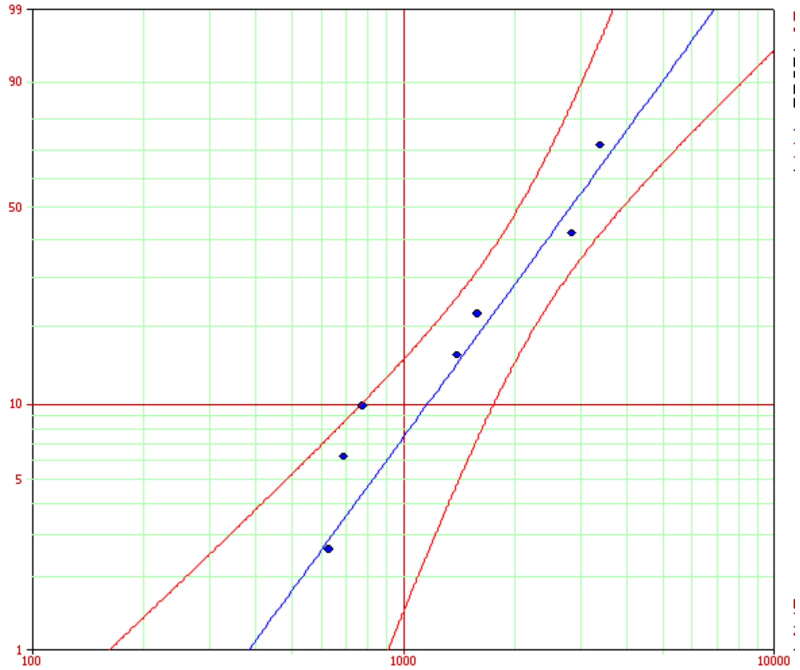

Figure 3

β ~ 2,12   and η ~ 3355,1

The corresponding Rocof has the following behavior:

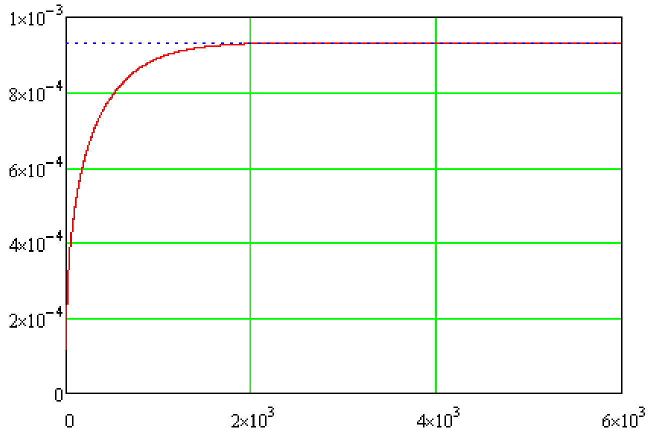

Figure 4

Noticeably, in the case of low shape parameter value (1 < β < 3), the asymptote is rapidly reached. A premature wear-out failure mechanism is then confirmed because the shape parameter β shows greater than 1 and the corresponding MTTF is very low as compared to the catalectic MTTF predicted by the FIDES methodology.
This result is not acceptable in terms of reliability, safety and maintainability. Indeed, the Rocof calculation implies that when a capacitor fails, it is replaced by a new one having the same characteristics i.e… a wrong polarity. This type of maintenance has no sense because the replacement should be performed by a new capacitor having the right polarity.

4.2 Replacement of the failed capacitor by an new and healthy one

The type of maintenance changes the Rocof expression as defined by equation (8). In this example, the following Rocof was obtained:

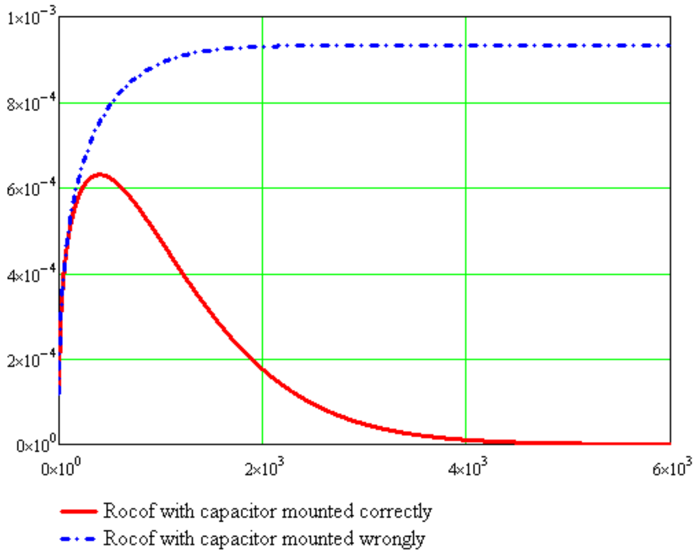

Figure 5

Note that the Rocof has an asymptotic value that tends to a catalectic failure rate.

4.3 Replacement of the failed capacitor based on any product failure

We have to define the right strategy i.e… retrofit or overhaul? The retrofit corresponds to a change of capacitors for all the products in the field. This operation is healthy from reliability, maintainability and safety points of view, but is very expensive and leads to a very bad image back to the customer.

Another possibility is the overhaul, which means that each capacitor with a wrong polarity is replaced by a capacitor with a right polarity whatever the failure on the product is. From equation (11), the following Rocof was obtained:

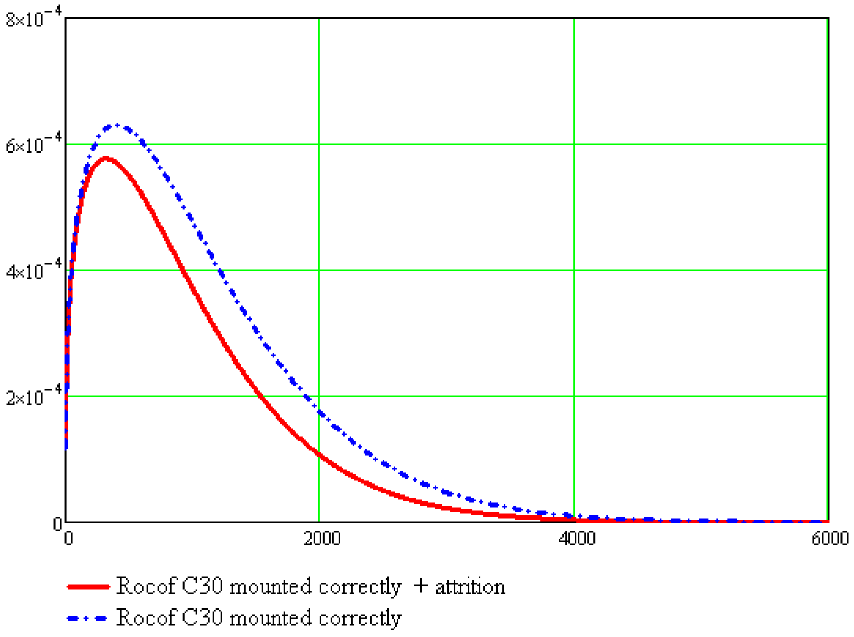

Figure 6

5 Conclusions

The paper shows, in case of premature wear-out failure mechanisms observed in the field, how to establish a strategy combining minimal costs and reliability, safety and maintainability objectives fulfillment. The applied theory is based on the renewal process and the corresponding reliability metric is the Rate of occurrence of Failure (Rocof).

In the particular - yet usual - case of Better Than New Maintenance, a corresponding Rocof expression is given that indicates the right strategy to be used, i.e. a simple corrective maintenance because the reliability, safety and maintainability objectives are always fulfilled, as compared to a retrofit because some or all the objectives aren't fulfilled and safety is challenged by an overhaul to maintain the objectives with minimal costs involved.

6 References

[REF 01] "Statistical methods for the reliability of repairable systems"
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[REF 02] FIDES guide 2009 Rev A
UTEC 80811

[REF 03] Tantalum Surface Mount Capacitors
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