Condition analysis of air conditioning cooling water pumps

S. Lampreia, V. Vairinhos & V. Lobo
Portuguese Naval Academy & Centro de Investigação Naval (CINAV), Alfeite, 2810 Almada, Portugal

T. Morgado
Laboratório Nacional de Engenharia Civil (LNEC), Instituto Politécnico de Tomar e UNIDEMI da FCT-UNL

ABSTRACT: In a ship, the operation of air conditioning system plays a prominent role in maintaining the operation of various electronic systems. Air conditioning system cooling water electropumps are rotating equipment that may be subject to degrading operating conditions. The electropump condition monitoring is a premise for maintaining the performance of air conditioning. For this, vibration measure is done on the electropumps. The objective of this paper was to define a statistic methodology to detect eventual anomaly in early stages. In phase I the collected data was analyzed and processed with Statistica and Matlab software. To obtain the functioning parameters, mean and standard deviation, the univariate Shewhart control charts: individual observation and moving range, were applied. In phase II, the monitoring phase, it was applied the Re-Modified CUSUM control chart. The application of statistic techniques can allow the knowledge of data tendency, and eventually define a future intervention.

1 INTRODUCTION

Cooling electro pumps from a ship air condition system are one important equipment for its properly functioning and for the ship itself. If it has a low performance the ship mission can be compromised.

A cooling electro pump maintenance plan can be preventive systematic by substituting some components (ex: sealing components) based on functioning time, or condition based on others (ex: bearings). The maintenance strategies will always depend on the electro pump lifecycle and the owner's financial capacity and its objectives for the systems. For example, considering owner in a bad financial context or if the system is on the end of life cycle, the implemented maintenance system can be a Risk Based Maintenance (RBM). A RBM system can be based on the results of equipment condition monitoring applied statistical methodologies.

On condition monitoring many non-destructives techniques may be use, for these electro pumps it is suggested to choose vibration monitoring with data registration and treatment.

Many statistical methodologies may be used, like modified control charts (Dias *et al*, 2009) and biplots, in this case and because of the results a re-modified CUSUM Control Chart will be used.

The main objective on this study is to predict, on time and continuously, the instant where a repairable equipment monitoring chosen parameter reaches a value of a failure.

2 STATISTICAL METHODS

2.1 *Phase I*

If there is a significate (200 or more) sample of the functioning parameters from an equipment, the Shewhart control charts will be applied, considering individual observations (X) and moving range (MR) control charts. With those charts, the parameters: mean and standard deviation will be estimated. If the data was not independent the ARIMA are suggested model (Lampreia *et al*, 2018a). The variables/parameters under study are considered continuous and independent (proven in the results), so the ARIMA models in this article will not be developed.

When the charts are design on phase I it should show under control variables, and if there are outliers it should applied statistical techniques to eliminate or integrate it.

Although the use of vibration monitoring, where the maximum values are controlled, and not the minimum, on table 1 for phase I the equations for the upper control limit (UCL), the lower control limit (LCL) and the center line (CL) for the Shewhart charts, are presented. This limits are calculated based on the m (or $m-1$) sample statistics, with the next equations:

$$\overline{X} = \sum_{i=1}^{m} X_i / m \tag{1}$$

$$\overline{MR} = \sum_{i=1}^{m-1} MR_i / (m-1) \qquad (2)$$

$$MR_i = |X_i - X_{i-1}| \qquad (3)$$

Table 1 – Shewhart Control Charts Limits - phase I (Requeijo & Pereira, 2012)

Chart	*LCL*	*CL*	*UCL*
X	$\overline{X} - 3\sigma_X$	$\overline{X}$	$\overline{X} + 3\sigma_X$
MR	$D_3\overline{MR}$	$\overline{MR}$	$D_4\overline{MR}$

If the process is under statistical control with all the observations between the control limits, its parameters should be estimated based on $\hat{\mu} = \overline{X}$ and $\hat{\sigma} = \overline{MR}/d_2$. The constants on table 1, D_3, D_4 and d_2 depend exclusively on the sample dimension and its values are defined on factors tables for variables traditional control charts defined by Shewhart. (Requeijo *et al*, 2012)

2.2 *Phase I – Modified CUSUM Chart*

The *CUSUM* control charts are based on "memory" statistics using the early results to calculate the present, it has high sensitivity to detect small shifts (Perry & Pignatiello, 2011). The analysis of an out of control in this charts must consider the values at present time and the values at the previous time. (Pereira and Requeijo, 2012).

For phase II it was tested the application of the modified *CUSUM* control chart for online condition monitoring, (Lampreia *et al*, 2016a), but accordingly the obtained results, it is proposed a re-modification of this charts.

A "Modified *CUSUM*" control chart is built on cumulative sum – *C* – (Lampreia *et al*, 2018b) like in the original *CUSUM* control chart (Sibanda & Sibanda, 2007) defined by:

$$C_t = max\left(0, C_{t-1} + (Z_t - k)\right) \;\; ; \;\; C_0 = 0 \qquad (4)$$

$$Z_t = \left(\left(\overline{X}_t - T_L\right)/\sigma_{\overline{X}}\right) \qquad (5)$$

$$\sigma_{\overline{X}} = \sigma/\sqrt{n} \qquad (6)$$

$$\Delta = \delta\,\sigma_{\overline{X}} \qquad (7)$$

$$k = \delta/2 \qquad (8)$$

$$T_L = (T_L)_{Standard} - \Delta_S \qquad (9)$$

$$\Delta_S = \delta_1\,\sigma \qquad (10)$$

where δ_1 is constant.

For this charts, $\overline{X}_t$ is the sample mean at *t*, T_L is the maximum admissible vibration, σ the process standard deviation, n the sample dimension, Z_t is the reduced form of $\overline{X}_t$, *k* the reference value and Δ_S the safety factor." (Barbosa, 2012) (Lampreia *et al*, 2018a)

For the "Modified *CUSUM* charts" it was considered two limits, one is an Alert Level (*AL*), and the second is the real Upper Control Level (*UCL*). The *AL* and *UCL* calculations are based on Gan (1991) abacus. It was considered a significance level $\alpha = 1\%$ ($ARL = 100$) to define the *AL* and $\alpha = 0{,}2\%$ ($ARL = 500$) to define *UCL* (Lampreia *et al*, 2016b).

2.3 *Phase II – Re-Modified CUSUM Chart*

Because of the obtained results using the given data, in the presence of high vibration values, considering a condition based maintenance implemented on the organization under study, it was decided to made a re-modification of the Modified CUSUM control chart so the results of the chart reflect the result of a high but maintained vibration, and doesn´t exponential the results. For that, it was applied a logarithmical base (e) and sum 5 units, Equation 8, considering and respecting the original chart limits.

$$C_t = \max\left(0,\ \ln(C_{t-1} + (Z_t - k)) + 5\right) \;\; ; \;\; C_0 = 0 \qquad (11)$$

For the Re-Modified *CUSUM* Charts it was considered the same two limits of the Modified *CUSUM* Control Charts.

3 METHODOLOGY

3.1 *Phase I - method*

a. Define the parameters to control.
b. Collect data to define the functioning parameters of the equipment.
c. Analyze the collected data, studying the continuity and independence.
d. If the data is independent apply the charts X and MR, and if the charts are under control define functioning parameters, mean and standard deviation.

3.2 *Phase II - method*

a. Apply the Re-modified *CUSUM* control charts for online condition monitoring.
b. Rules for intervention, Figure 1:
   - ✓ If 10 sequential observations between the AL and the UCL or/with less than 4 sequential above the UCL proceed to a more frequently observation.
   - ✓ If 4 observations above the UCL proceed to an intervention of maintenance.

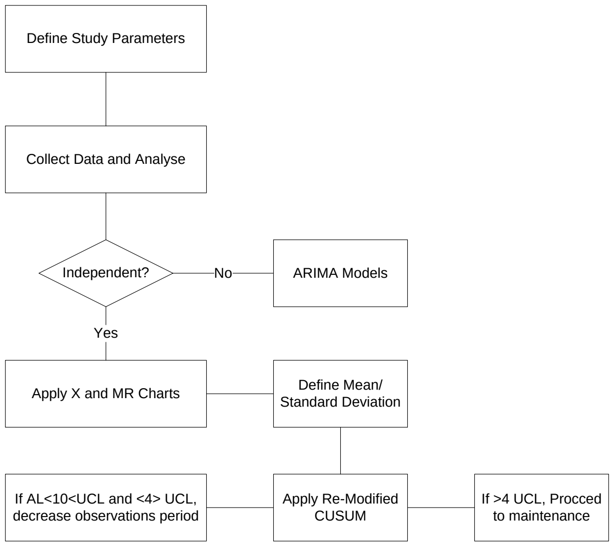

Figure 1. Condition Monitoring Methodology

4 CASE STUDY

The electro pump under condition monitoring is part of the air-condition (AC) ship system. In the ship there is four refrigerated pump, two for the forward AC and two for the backward. For this system a preventive maintenance plan is defined. Usually the anomalies are early detected with vibration measures. The study will be about an electro pump with a detected anomaly.

It was defined two points of measure of the electro pump, point A and point B, Figure 2. Because of the interesting results, with a registered anomaly, for data treatment the axial and vertical observations of the two selected points was chosen, and decline the horizontal data. In the article the point with better results is the A-V.

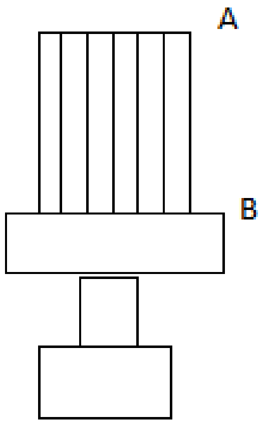

Figure 2. Electro-pump points of measure.

After test the data independence on Statistica software applying the autocorrelation function, it was concluding that the data was independent, so the collected data is directly used on the control charts.

Originally, and because there is lack of data registration, data was simulated on Matlab, for phase I based on data without an anomaly in the pump and in phase II considering an anomalous state and based on simulation on real data.

The normality of data was checked with Kolmogorov-Smirnov test (for $\alpha = 5\%$); and for A-V: d= 0,04584. Since $d < D_{Crítico}$ the data was considered normal.

$$D_{Critical} = \frac{0,886}{\sqrt{N}} = \frac{0,886}{\sqrt{200}} = 0,0626$$

Phase I

On phase I the parameters was defined, in Figure 2 and Figure 3 represent respectively the Control charts for individual observation and the moving Range Control Chart using the Statistica software. When all data was between the control limits the functioning parameters for the vibration were defined.

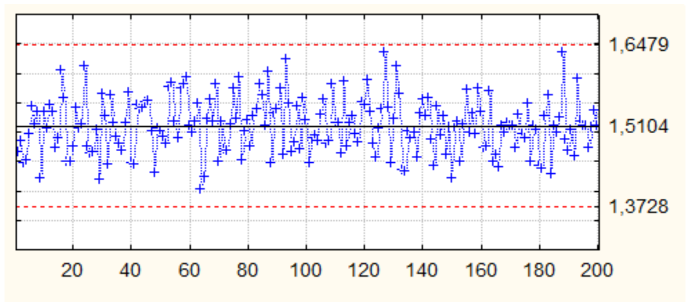

Figure 3. Control chart for individual observation point A-V

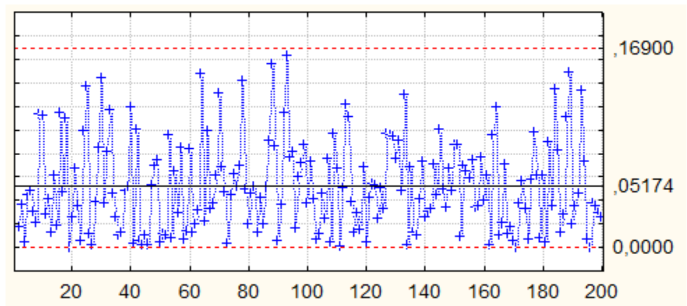

Figure 4. Control chart for Moving Range observation point A-V

The definition of the parameters was made for the four observation axis considered for the study, where was obtained the mean and standard deviation for each one, Table 2.

Table 2. Variables - Parameters.

Point/Obs	μ	σ
A-A	1,0833	0,04591
A-V	1,5104	0,04585
B-A	1,1397	0,05216
B-V	1,5320	0,05025

When the parameters were defined, it was passed to phase II.

Phase II

Analyzing the obtained data, the highest measures of the four selected points for study was for point A-V and for point B-A.

The graphical results are presented for A-A and A-V.

The limits of the Charts for phase II are on Table 3:

Table 3. Variables - Parameters.

		ARL	
		500	100
		LSC (α=0,2%) **h**	LA (α=1%) **h1**
K=δ/2	0,25	8,5	5,51
	0,5	5,1	3,5
	0,75	3,5	2,5

In phase II it was used the re-modified *CUSUM* control chart because the modified CUSUM control chart wasn´t adequate, because the values were already too high for the chart design, all the data was above the UCL, notice that the UCL it is 8.5 and the first result it is above forty, Figure 5.

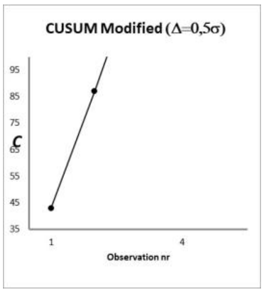

Figure 5. Modified CUSUM Control Chart for A-V observation point

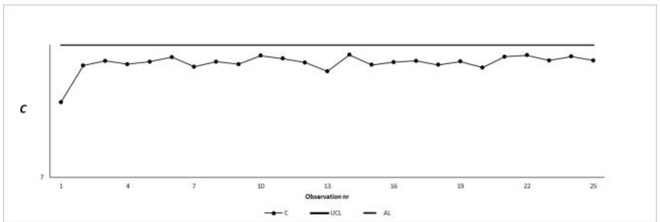

Figure 6. Re-Modified CUSUM Control Chart for A-V observation point

On Figure 6 and 7 the observations correspond to vibration measure on point A of the electro pump.

For Figure 6, only the UCL is represent, but the results were all between the Alert Level and the UCL, so the electro pump monitoring should be more frequently since observation nr 10.

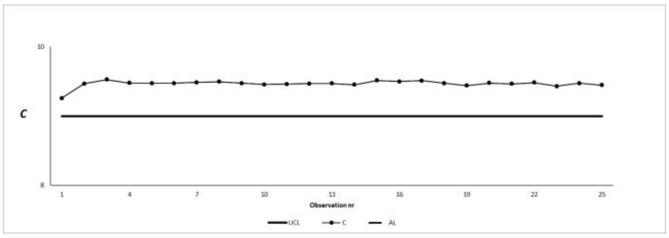

Figure 7. Re-Modified CUSUM Control Chart for A-A observation point

For Figure 7, considering a CUSUM Modified (Δ=0,5σ) it also represents the UCL, but the results were all above UCL, so accordingly the defined methodology there is a need to proceed to maintenance intervention of the electro pump since observation nr 4.

Because of time limit reasons, it was not possible to simulated other data and test this re-modified charts on other equipment'. Work will be done to obtain more real data from the condition monitoring realized by the ships to try to take more real evidences of these results.

5 CONCLUSIONS

The performance of cooling electro pump is important for ship operation and systems functioning.

In a same equipment, various maintenance systems can be integrated considering its various components.

Using vibration measure the condition of the electro pumps may be defined.

The collected vibration can be treated with statistical techniques, with a re-modification on the Modified *CUSUM* control Charts.

It was considered two phases of the control charts application (phase I and phase II), on phase I historical data was used, and for phase II it should proceed to an online monitoring.

It charts may be applied in order to obtain early damage tendencies. But in this specifically article for control charts it is recommended complemented tests and simulation in others equipment's.

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