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# EQUIPMENT CONDITION MONITORING WITH AN APPLICATION OF MEWMA CONTROL CHARTS AND OTHERS CHARTS

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**Abstract.** *The degradation of electromechanical systems is a continuous process that must be prevented. In order to minimize losses and the increase of maintenance costs, conditioning monitoring should be applied to critical equipment (Condition Based Maintenance - CBM) [1]. Conditioning monitoring can use statistical methods to estimate the present state of the collected data. The Accelerated Failure-Time Models can be an important method for prediction system failures. In this paper collected data are vibration values, obtained with overall vibration values (RMS) from four points from an electropump, and in a second phase, a failure will be induced to degrade the equipment state. When variables are not independent, it is suggested modeling data with ARIMA (p, d, q) models [2], and use the residues for the first Phase. In the Phase I, the estimation of parameters is achieved using the traditional Shewhart charts. The combination of the four variables, T2, is performed only after the ARIMA model is estimated. The special multivariate control charts are used to predict failures. Assuming independence and Normal Distribution, MEWMA Modified Control Charts [3] will be applied in the Phase II to new collected data, by this procedure, behavior of the equipment will be controlled. In phase II, if the data are dependent, the prediction errors are used. The previous methodology is used just for fault detection. Using a chart expressing vibration as a function of velocity (m/s) it will probably possible to make diagnosis and identify which component is causing vibration. Using these methodologies allows online condition monitoring and act in time to minimize maintenance and outage costs.*

## 1 INTRODUCTION

When there is a project to implement a condition based maintenance system, the type and equipment performance must be considered. The main target is to reduce maintenance costs and optimize operation.

To have a highest level of the equipment state, statistical methods are applied. The objective is to categorize anomalies, identify components involved, estimate possible tendencies and predict the time to failure. [1]

To test systems reliability Weibull model and Laplace test is used. [4]. By these methods we can study the system failure tendency.

Considering repairable systems the data collected and processed by statistical methods can be collected by sensor installed in key points, and it can be a fixed one, or portable.

When we decide the parameters to measure in equipment, we believe that that are the ones that best represent the equipment behavior. In this subject, also many can be chosen, in spite of temperature and pressures in sensors/manometers, in rotating equipment's vibrations, oil analysis, thermography can be the most representative of its states [5], both are suggested because it doesn´t needed any intervention during the collet action. In the present study, the vibration was the elected.

In this work a portable vibration collector was used, the uploading of data being controlled using the equipment software. To define the vibration parameters and monitoring the Statistical Process Control (SPC) with some modifications was applied. To diagnosis the detected anomaly graphical representations were built represented frequency vs speed.

## 2 CONTROL CHARTS

Given the right conditions, multivariate control charts can be applied for process control. In this work, Hottelling Chart, $T^2$, was used to equipment monitoring in first phase, to check the equipment stability and define it´s parameters, and in the second phase the *MEWMAM* control chart will do the monitoring.

### 2.1 Phase I - $T^2$ Traditional Control Charts

The design of the $T^2$ charts obey to some rules, at first, more than one variable should exist, and then enough data should be collected to estimate the process parameters. Because of the data specifications, individual observations (*n=1*) charts will be used. [6]

### Independent Data

If the observations of $p$ variables in control are independent, we have, $X_{ij} = \mu_j + \varepsilon_{ij}$ , where $X_{ij}$ is the observation *i* for *variable j,* $\mu_j$ is the process mean for the variable $j$ , $\varepsilon_{ij}$ are *iid* normal random variables with mean zero and standard deviation $\sigma_\varepsilon$ (white noise).

In phase 1 with *m* individual observations collected, $X_{jk}$ ( $j = 1,2,\ldots,p$ and $k = 1,2,\ldots,m$ ), the mean, ( $\overline{X}_j$ ), the variance ( $S_{ij}$ ), and the covariance $S_{jh}$ are calculated. Based on this statistics, the vector mean ( $\bar{X}$ ) and the covariance matrix (*S)* are given by the next expressions:

$$\bar{X} = \left(\bar{X}_1, \bar{X}_2, \ldots, \bar{X}_p\right)^T \qquad S = \begin{bmatrix} S_{11} & S_{12} & S_{13} & \cdots & S_{1p} \\ S_{21} & S_{22} & S_{23} & \cdots & S_{2p} \\ . & . & . & \cdots & . \\ . & . & . & \cdots & . \\ . & . & . & \cdots & . \\ S_{p1} & S_{p2} & S_{p3} & \cdots & S_{pp} \end{bmatrix} \tag{1}$$

For each *k* the $T^2$ control charts are based on the statistic in the expression 2, as follows:

$$\left(T^2\right)_k = \left(X_k - \bar{X}\right)^T S^{-1} \left(X_k - \bar{X}\right) \tag{2}$$

The *Center Line (CL)* and the *UCL* for the phase I are defined in Table 1. The expression $\beta_{\alpha;p/2;(m-p-1)/2}$ is the right percentile, for a probability $\alpha$, from the beta distribution with the parameters $p/2$ , $(m-p-1)/2$ . The rule applied to estimate the parameters for $T^2$ Control Charts in phase I, is to have the sample size *m* ( $180p \le m \le 300p$ ). [3]

| Chart | *CL* | *UCL* |
|---|---|---|
| Phase I | 0 | $\frac{(m-1)^2}{m} \beta_{\alpha;p/2;(m-p-1)/2}$ |

Table 1: $T^2$ Control Chart Limits.

## Autocorrelated Data

If a variable has a significant autocorrelation, the $T^2$ statistic is estimated using the residues to every observation. The parameters $X_k$ , $\bar{X}$ and $S$ are replaced with the corresponding residues and the mean vector and covariance residues matrix are built. To calculate the residues is built a model with correlated variables, so the *ARIMA (Autoregressive Integrated Moving Average*) (*p, d, q*) model is applied. [6]

The process autocorrelation is analyzed studying the Autocorrelation Function (*ACF*) and Partial Auto-Correlation Function (*PACF*). To decide which model we have, the estimated autocorrelation function (*EACF*) is compared to the autocorrelation function (*ACF*) and the estimated partial autocorrelation function (*EPACF*) with the partial autocorrelation function (*PACF*). [3] [7]

A process follows a *ARIMA* (*p,d,q*) model if $\nabla^d X_t$ follows *ARMA*(*p,q*) model. The model defined by *ARIMA*(*p,d,q*):

$$\Phi_p\left(B\right)\nabla^d = X_t = \Theta_q(B)\varepsilon_t \tag{3}$$

$$\Phi_p\left(B\right) = (1 - \phi_1 B - \phi_2 B^2 - \ldots - \phi_p B^p) \tag{4}$$

$$\Theta_q(B) = (1 - \theta_1 B - \theta_2 B^2 - \ldots - \theta_q B^q) \tag{5}$$

$$B = \frac{X_{t-1}}{X_t} \tag{6}$$

$$\nabla = \frac{X_t - X_{t-1}}{X_t} \tag{7}$$

See [3] for details.

The residues for the specified model are estimated by $e_t = X_t - \hat{X}_t$, where $\hat{X}_t$ is an estimation of the process expected value for the period *t*. The $T^2$ control chart is built using the residues. The process mean is estimated by equations 7 and 8 when the process is modeled by an *AR*(*p*) or by a *MA*(*p*).

$$E(X) = \mu = \frac{\xi}{1 - \sum_{j=1}^{p} \phi_j} \quad (7) \qquad\qquad E(X) = \mu \tag{8}$$

## 2.2 Phase II - Special Control Charts – Modified *MEWMA*

The use of cumulative charts is chosen instead of traditional control charts, given its sensibility to small changes.

The *EWMA* multivariate control chart, *MEWMA*, to control the mean is based on the $T^2$ statistics, defined, for the *i* instant by:

$$T_i^2 = Z_i' \textstyle\sum_Z^{-1} Z_i \tag{9}$$

where

$$Z_i = RX_i + (I - R)Z_{i-1} \quad , \qquad Z_0 = 0, \qquad \textstyle\sum_Z = \frac{\lambda}{2-\lambda}\left(1 - (1-\lambda)^{2i}\right)\sum \tag{10}$$

In this equation, $I$ is the identity matrix and $R = diag(\lambda_1, \lambda_2, \ldots, \lambda_p)$, where $\lambda_j$ ($j = 1, 2, \ldots, p$) is a weighted constant from the $j$ variable. Usually $\lambda_1 = \lambda_2 = \ldots = \lambda_p = \lambda$, when this happen, $Z_i$ is defined by:

$$Z_i = \lambda X_i + (1 - \lambda) Z_{t-1} \tag{11}$$

Since data is autocorrelated and we are applying the *MEWMA,* the next expressions will be used:

$$Z_i = \lambda(e_i - T_L) + (1-\lambda)Z_{t-1} \qquad\qquad \Sigma^{-1}(\lambda(e_i - T_L) + (1-\lambda)Z_{t-1}) \tag{12}$$

An out of control situation is detected when $T_i^2 > H$, where $H$ is the control limit.

In [8] the values of *H* for $ARL_{In\ Control} = 200$ and for $\delta(\mu)$ are suggested when: $p = 2,4,6,10,15(0,5;1,0;1,5;2,0;3,0)$ and $\lambda(0,05;0,10;0,20;0,30;0,40;0,50;0,60;0,80)$.

From the same reference optimal values for *MEWMA* chart can be obtained, the best values λ and *H* for $p = 4,10,20$ are for $ARL_{In\ Control} = 500$, $ARL_{In\ Control} = 1000$, for different values of $\delta(\mu)(0,5;1,0;2,0;3,0)$.

*MEWMA* chart, like univariate *EWMA* chart, shows a high sensitivity compared with $T^2$ and $\chi^2$, and considering small and moderate shifts. [9]

## 3 ANOMALIES DIAGNOSIS

Vibrations are caused by periodical events-namely, anomalous events in the machines; its frequency can allow the anomaly diagnosis. [9] Vibration measure and analysis can allow the detection of most faults and an early stage, detecting faults without systems stop, and diagnose the cause of malfunction [10]. Although, vibrations can be characterized by: displacement, velocity e acceleration, in this work we will use the velocity (mm/s) measure.

The cause of vibration can eventually be found, inspecting the frequency spectrum where frequency is expressed by orders. For example: if we had a misalignment, we can find peaks at 1x, 2x and sometimes at 3x.

In this work abnormal frequencies will be analyzed; given the , extension of the field, only a partial vision will be presented. For more information Institute (2005) and Eshleman (1999) should be consulted.

## 4 METHODOLOGY

1. To define the methodology for monitoring data, sample size (m) is a fundamental input for specified statistical procedures.
2. In phase 1 study the data independence, comparing *EACF* and the *EPACF*. If data is autocorrelated, the *ARIMA* model should be applied, and the $T^2$ chart is executed for the residues; if not the original data are used. When distribution is Normal and stable the mean vector and the covariance matrix are calculated. For this phase at least 200 samples of individual observations must be taken.
3. In the Phase 2 the *MEWMAM* chart is used to monitor the equipment. In this phase the equipment´s are monitored since the first observation, and only under defined rules actions are taken. To define the rules, the $T_{LStandard}$ described above should be evaluated according international standards or manufacture´s rules. [7] To define the chart limits:
    - Estimate the two limits to control the mean level of vibration, specifically, the Upper Control Limit (*UCL*) and the Alert Value (*AL*).
    - Based on ISO 2372:2003 Standard, establish the vibration level which the system must have an intervention.
    - Rules to act on the system:
        - Execute an intervention to detect any anomalous situation when 8 consecutive points are above the *AL*.

- Proceed to a maintenance intervention when 5 consecutive points above *UCL* are observed.

4. To proceed with the intervention act, we should know which the anomaly is, so the frequencies spectrum in order to velocity (mm/s) chart must be observed.

## 5 CASE STUDY

For the case study, vibration data from an electro pump was used. Four points were defined for data collection to represent the machine state.

To test the *MEWMA* sensitivity an anomaly with four state aggravations was forced. The vibration values are expressed in units of velocity (mm/s) for vibration global values (RMS).

For Phase 1, considering the electropump working properly, in Phase 1 the equipment parameters are estimated based on 241 individual observations. The first step is testing the data independence, comparing the *EACF* and *EPACF* with the *ACF* and *PACF*, for four variables, the result being a model that best feats the data. The result is that we have autocorrelated data, so we use the residues in the *Shewhart* control charts. The residues are estimated using the *Statistica* software. Treating the data independently for the Var2, was detected a point above the *UCL*, so it was substituted using the defined model. Figure 1 shows the *EACF* and *EPACF* for the variable 2, where autocorrelation is significant and we can see the *AR2* ARIMA model, where for *ACF* we have an exponential decrease after a certain lag order, and *PACF* for significant peaks through lags log (p).

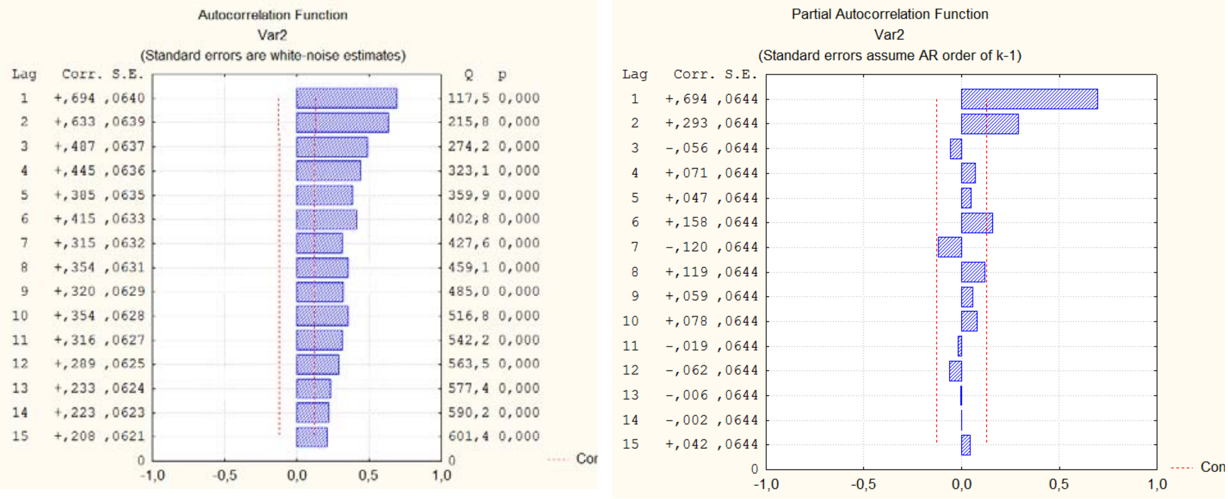

Figure 1: *EACF* and *EPACF* for Var2.

All the four variables are well fitted *AR*(2) *ARIMA* model, given space limitations we show values corresponding only to Var2: $\xi$=0,1025, $\varphi_1$=0.4945 and $\varphi_2$=0.2919.

Although, not presented in hear, all variables has been studied and have a Normal Distribution. When we analyze the $T^2$ Chart, no special causes of variation are detected, so the mean vector (residues and variables) and covariance matrix are estimated. [3] For of graphic quality reasons, in figure 2, only 100 of the 241 samples are present.

$$\bar{e}=\begin{bmatrix}0,00033\\0,00021\\0,00034\\0,00041\end{bmatrix}\qquad \bar{X}=\begin{bmatrix}0,406\\0,4810\\0,7400\\0,5220\end{bmatrix}\qquad S=\begin{bmatrix}0,000726 & -0,000057 & 0,000137 & 0,000035\\-0,000057 & 0,000686 & -0,000123 & -0,000007\\0,000137 & -0,000123 & 0,007102 & 0,000298\\0,000035 & -0,000007 & 0,000298 & 0,001627\end{bmatrix}$$

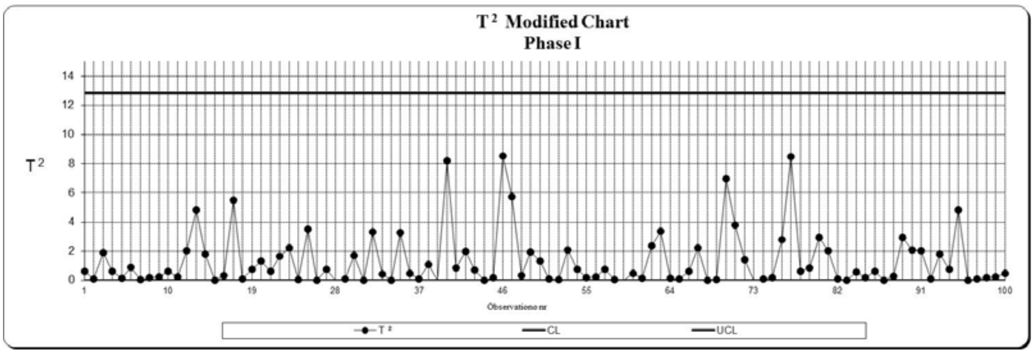

Figure 2: Phase 1 - Modified $T^2$.

For phase 2 the limit vibration was extracted from the ISO 2372:2003, and for an electrical engine with 1,5KW, 1.12 *mm*/s (*RMS*) is the allowable limit of an equipment of class I. It will be named as $(T_L)_N = 1{,}12$.

Having *p=4*, according Crowder (1989) abacus, the limits for *MEWMAM* charts are presented in table 4, so the *K*1 is the Alert Level (2,1) and *K* (2,7) the Upper Control Limit, table 3.

The vibrations are monitored since the first data value. To test the chart sensitivity, 50 individual observations were read with the electric pump in normal operation; then, to accelerate the degradation, an anomaly and its aggravation through 4 stages was introduced.

Building the *MEWMAM* chart to monitoring the equipment, till the second aggravation no point is registered in the charts.

For the third aggravation was registered 3 points, but all of them are under control the *UCL*, Figure 3.

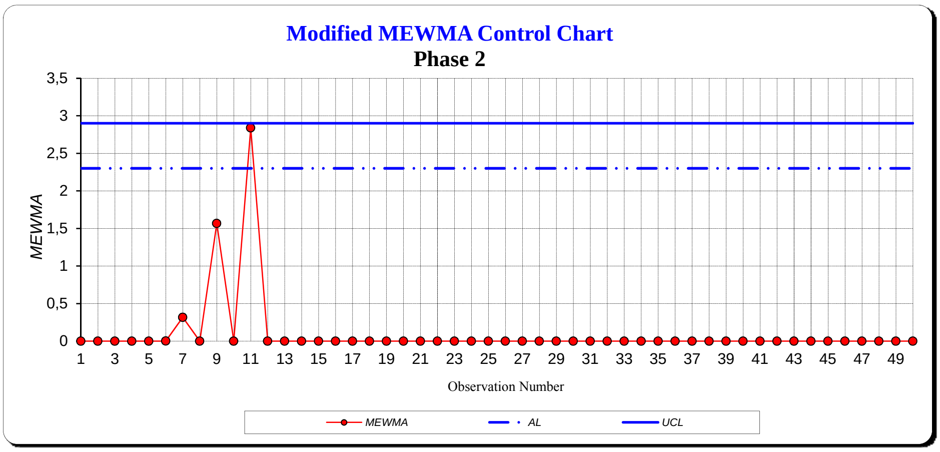

Figure 3: 3ª Aggravation *MEWMAM* Control Chart.

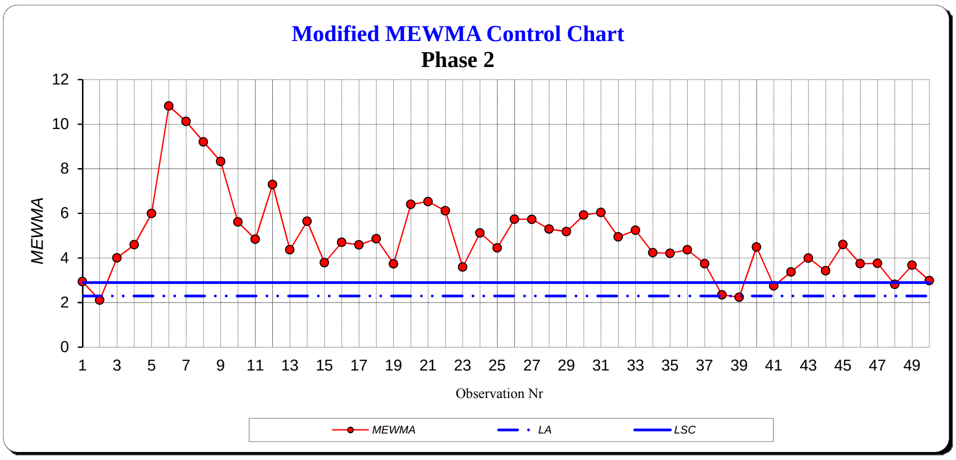

Figure 4: 4ª Aggravation *MEWMAM* Control Chart.

The use of *MEWMAM* control charts shows a high level of sensitivity since the third observation, almost all of the data are above the upper control limit, figure 4.

For frequency spectrum analysis we must know the electro pump characteristics, as we saw, power is 1,5 KW, the velocity is 1500rpm, and the natural frequency is 25Hz. The results from the analysis are shown only for Var2. With no anomalies, only appeared the natural frequency at 25Hz. We have also signs of resonance between the 1750Hz and 2250Hz and between 2250Hz and 2750Hz.

For the first state aggravation no big changes detected. In the second aggravation the values of vibrations became higher and a peak can be seen at 300Hz (12x), figure 5. Now the resonance appears between 1750 and 2250Hz.

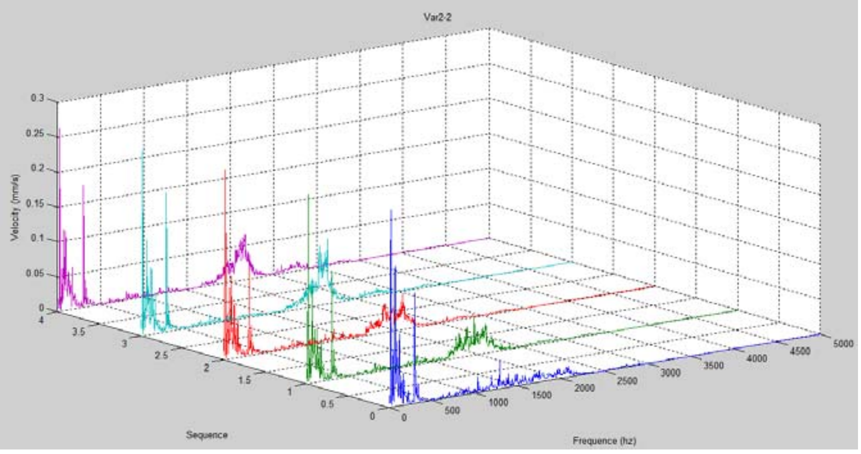

Figure 5: Var2 Data Analysis – 2th Aggravation.

Given the detected peaks, we may probably be having problems, for example: a clearance bearing problem, a shaft eccentricity or blades anomaly.

By the 3rd aggravation the values take significantly higher values. The 4th aggravation is just a development of the 3rd aggravation, where the peak at 300hz has a 0,13mm/s increase (12x), figure 6. The peaks with 25hz and 75hz had get higher too, that represent the 1x and 3x orders.

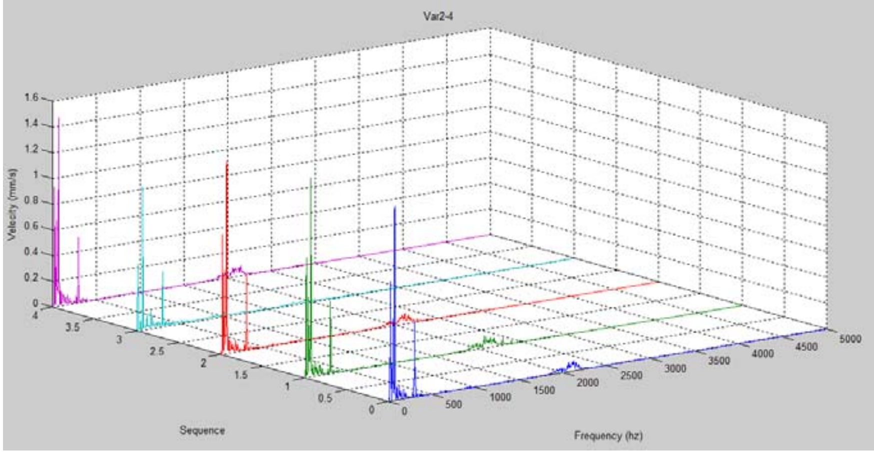

Figure 6: Var2 Data Analysis – 4th Aggravation.

The natural frequency is 25hz, so we believe the peaks around this frequency are a consequence of the unscrewing. The causes are not explained by just one anomaly but to the whole set of misalignment but from various, misalignment between the pump and the electrical engine, imbalance in rotors, etc. If this was a real equipment which was being monitored, the situation should be monitored to detect a tendency. In case of a continuous aggravation it is recommend to see the tendency, if the aggravation continuous it is recommend to disassemble the electropump, do the dimensional control of the spare parts and repair or replace the damaged ones.

## 6 CONCLUSIONS

In equipment monitoring many mechanical and thermodynamics methods can be used to get data In this article we explore the Statistical Process Control in equipment´s monitoring.

To Phase 1, autocorrelated data was collected. So the $T^2$ charts were applied using the residues from a fitted *ARIMA* model..

In Phase 2, the *MEWMA* were applied to the expected values, high sensitivity since the 3rd aggravation was shown.

Although the results, more tests, and maybe application to others equipment´s, should be carry out.

Applying the control charts, we knew the equipment had an anomaly, but didn´t know which one. To diagnosis the anomaly, a cascade graph using the frequencies and velocity registered, has shown a possible cause for the high observed vibration values.

We believe that the control charts application and the spectrum analysis is an effective monitoring method, knowing its real state and its tendency. This will enhance the performance of the maintenance, reducing the costs and raising the availability.

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