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Analysis of Recurrent Failures and Proposal of Solutions for the Water Pumping System

Análisis de fallas recurrentes y propuesta de soluciones para el sistema de bombeo de agua

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ABSTRACT: Shrimp is a product of high commercial value in the international market and its production shows a remarkable growth. The main support of its culture medium is water. Water of good quality leads to good growth, survival and good production of shrimp. To make this happen, the items, which play a fundamental role, are water pumps. An unexpected failure in this equipment can affect or even significantly compromise the production. In the present work the causes of electrical and mechanical failures and deficiencies in the maintenance occurred in the axial pumps, belonging to the Enterprise for the Cultivation of Shrimps were investigated. Maintenance engineering processes was carried out, a SWOT matrix was applied and important economic aspects were analyzed. Finally, recommendations were made to reduce the failures and improve economic aspects; obtaining some benefits already.

Keywords: Shrimp C, Maintenance, Failure Analysis, Pumping System, Diagnosis.

RESUMEN: El camarón es un producto de alto valor comercial en el mercado internacional y su producción presenta un notable crecimiento. El soporte principal de este medio de cultivo es el agua. Un agua de buena calidad conlleva al buen crecimiento, supervivencia y buena producción de los camarones. Para lograr que esto ocurra los equipos, que juegan un rol fundamental, son las bombas de agua. Una falla o avería imprevista en estos equipos puede afectar o inclusive comprometer de forma importante la producción. En el presente trabajo se investigaron las causas de las fallas eléctricas, mecánicas y de deficiencias en el mantenimiento ocurridas en las bombas axiales, pertenecientes a la Empresa para el Cultivo del Camarón. Se realizaron procesos de Ingeniería de Mantenimiento y se analizaron aspectos económicos importantes. Finalmente se brindaron recomendaciones para disminuir las fallas y mejorar los aspectos económicos; obteniendo ya, actualmente, algunos beneficios.

***Palabras clave*:** cultivo del camarón, mantenimiento, análisis de fallas, sistema de bombeo, diagnóstico.

INTRODUCTION

The cultivation of aquatic organisms on a large scale is a relatively recent event although on a small scale this activity has existed since ancient times in several countries, most likely from the origins of grazing and agriculture.

In companies that cultivate shrimp, vertical axial pumps with a diameter of 24 inches were initially installed, with a flow rate equivalent to 1000 L/s. In 2012, electric pumps with higher efficiency were installed to complete the pumping capacities and, at the same time, to replace the pumps previously installed, that did not have the optimum operating parameters, allowing improvements in the filling and replacement of the water in the ponds and the possibility of sowing greater densities of animals per square meter.

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Since the first installation carried out, the new pumps acquired showed systematic failures, both electrical and mechanical.

The subject of the following investigation was, therefore, to identify the causes of the systematic failures that occurred in the newly acquired axial electric pumps of the shrimp companies and to recommend solutions to achieve their elimination or reduction.

METHODS

The present work entailed the realization of different research tasks, whose methodological procedure, in an orderly manner, are described below.

The following scientific tasks were considered:

Analysis of the state of the art (in updated bibliography of the subject in question).

To carry out the work, an in-depth bibliographic study was carried out on the subject in publications carried out in Europe by Stern *et al.* (1990), in Asia by Atwood *et al.* (2003) and Boyd and Thunjai (2003). In Latin America works by Arredondo and Ponce (1998) and Borja (2011) were studied as well as others in the United States by Boyd *et al.* (2002) and Atwood *et al.* (2003), together with other authors (Ayers and Westcot, 1976; Tamayo, 1998; Zhu *et al.*, 2004, 2006; Akilov *et al.*, 2009; Barriga, 2011; Assan and Kléber, 2014).

Criticality Analysis to Detect the Company with the Greatest Faults

Criticality analysis is the methodology that allows hierarchizing systems, facilities and equipment, according to their global impact, in order to facilitate decision-making. For the selection of the evaluation method, engineering criteria, weighting and quantification factors were taken. For the application of a defined procedure it is about compliance with the application guide that has been designed. Finally, the hierarchical list is the product obtained from the analysis (Mendoza, 2005; Prat Planas, 2014).

Based on the geographical distribution of the Company, the objective of the project was to perform a criticality analysis to establish the level of hierarchy of the 5 shrimp producing companies. In this way, an accurate orientation was obtained for the development and application of the project and the technical and maintenance diagnosis was made in the shrimp farms that were more critical. The general characteristics of these companies is that they have from 2 to 15 vertical axial flow pumps that vary between 1 and 1.2 m³, generally installed between 1 and 3 pumping stations and responsible for guaranteeing water to shrimp development ponds. In 93% of pumps, the energy used by motors is electric power. Failures of the pumps have occurred in all the companies.

The categories evaluated in the criticality analysis were:

- The failure frequency (F.F). To estimate it, the records of the frequency of failure in number of events during the period analyzed (2012 - 2016) were used and the pump operators were consulted.
- Production levels (NP). This factor considered the shrimp production levels of each company.
- Environmental impact (IA). This category considered the possibility of occurrence of undesired events with damage to the environment.
- Repair costs (CR). The repair costs of the faults presented by the pumps were considered.
- Equipment Replacement Costs (CE). It considered the number of pumps purchased by the inve stment process multiplied by the purchase price of each of them at the time they were purchased in the period analyzed (2012 - 2016).

The mathematical equation used to assess the criticality was:

Criticity = frequency x consequence according to Mendoza (2005), where the consequence was conceived as the sum of all the factors in which the faults have a negative impact, giving rise to equation 1.

$$Criticity = FF\,x\,(NP + IA + CR + CE) \quad (1)$$

The result obtained was represented in a bar graph where the companies were located on the axis of the ordinates and the criticalities on the abscissa axis.

Technical Diagnosis Based on the Analysis of:

a. Installation of network analyzers to make measurements of electrical parameters.

b. Reading of the level of vibrations of the motors.

c. Checking of eccentricity and permanent deformation by axis bending.

In order to know the nature of the mechanical and electrical problems that occurred in the pumps, measurements of the symptom parameters of the pumps were made.

a. Installation of network analyzers to make measurements of electrical parameters.

The installed pumps have soft starters to handle the starting of electric motors. The quality of the supply or more specifically, a disturbance of the quality of the supply, is defined, in general, as any change in the supply, voltage, current or frequency that interferes with the normal operation of the equipment or electrical component (Horsley, 2009).

From this definition, the parameters measured were the supply and current consumption voltages of the electric motors and in the technical operation measurements of the vibration level of the pumps were made and the alignment of the axes of the pumps was measured.

To perform the measurements of the electrical parameters, an AR-5 Circutor network analyzer was installed, programmed to obtain the data for a period of one week. The programming considered the reception of the parameters voltage and current of consumption under normal conditions of work of the pumps. Those conditions were: nominal voltage of the motor, with a value of 460 V of alternating current ± 5%, specified by the manufacturer; imbalance of phases, using NEMA Standard MGI.1993 (Tiwari and Bhardwaj, 2014) and IEEE according to Oqueña and Ciro (2003), where equation 2 is used to calculate the% of imbalance between phases:

The state of the voltage imbalance was also measured by taking the difference between the highest and lowest voltage of the three power phases. This number should not exceed 4% of the lowest voltage. Another parameter programmed to be measured with the analyzer was the power factor. The latter, although it is not a symptom parameter of the analyzed equipment, it does constitutes an indicator of the energy efficiency of the pumping stations. In industrial installations, where the load is mainly associated with large induction motors, a backward power factor is generated. For that reason, it is necessary to compensate the inductive load with capacitive load, in addition to making modifications or actions for the motors to operate in conditions of suitable load (75 to 100%), to manage the total load factor of them and of the installation (Campos, 2010).

b. Reading of the level of vibrations of the motors.

For this, the application of a digital vibrometer was used, which consists of a scale of 12 levels of vibrations ranging from the Instrumental I scale: vibrations perceptible only by animals to the Cataclysmic XII scale: total destruction (Chen *et al.*, 2017). The vibration values obtained were compared with the one allowed by the manufacturer, which states that it must be in the vicinity of scale II (Chen *et al.*, 2017). The measurements were taken at the base of the upper anchor plate and at the anchor base with the concrete base. With the level of vibrations of the equipment, it was possible to have an idea of how the equipment is anchored, or adjusted in the motor-pump coupling or the motor-transmission system alignment.

c. Eccentricity check and permanent deformation by axes bending.

The flexible couplings solve problems of axial and angular misalignment, sudden loads among others. It also potentially reduces vibrations (Penkova, 2007).

To verify this aspect, a caliper gauge was used. This measuring tool allows knowing the distance that is required between axes in the vertical and horizontal planes in millimeters to be able to take the motor shaft and the pump axis to center. The parameters obtained were compared with the specifications offered by the manufacturer in the pump (Penkova, 2007). Another aspect that was proved was that of the axes with respect to their

$$Percentage\ \ of\ \ imbalance = \frac{maximum\ \ voltage\ \ deviation\ \ with\ \ respect\ \ to\ \ average\ \ voltage}{average\ \ voltage}.100 \quad (2)$$

points of support. To carry out this measurement, a watch-type gauge or dial gauge was used.

Diagnosis of the maintenance activity from the analysis of the data obtained from:

- Tour and visual inspection carried out.
- Compilation of information contained in work orders and equipment records.
- Application of surveys to technicians and operators of pumping equipment.
- Analysis of the fault history that took place in the pumping equipment
- Identification of the causes of pump equipment failures.

The quality of the maintenance and the way of operating an industrial installation is reflected in the technical state in which it is in each time. In this way, if the operations and maintenance personnel work optimally, the plant will remain in good condition during the life estimated initially, even much longer. However, if one of these areas is not managed correctly, the installation will suffer, decreasing reliability, availability and useful life (Green *et al.*, 2009).

The files reviewed were those of the pumping equipment, the areas covered were the pumping stations and maintenance workshops of the selected companies. The surveys were applied to personnel directly linked to the maintenance area in those companies. The evaluation of factory maintenance was applied, focusing said evaluation towards the pumping activity.

To diagnose the maintenance activity, some of the existing methodologies were used to audit the Maintenance Management exposed in PDVSA Audit Model (Green *et al.*, 2009). They are based on questionnaires and evaluations to be applied to all personnel of Organization (Maintainers, Group Leaders, Functional Directors), as well as on-site maintenance evaluation.

Surveys were applied to all the personnel chosen, which allowed obtaining information and a vision of the behavior of the maintenance function, through the completion of the questions printed in the applied questionnaire (Green *et al.*, 2009).

The information collected was evaluated qualitatively and quantitatively. In order to carry out the qualitative analysis, annotations derived from direct observation and from the study of documents were taken, which allowed positioning the chosen factors in each of the corresponding maturity stages of the MCM matrix. To validate these annotations, they were compared with the results of the surveys and the evaluation of the maintenance carried out quantitatively. For the quantitative evaluation, a points system was used that was given to each of the categories analyzed and compared with the base points. Subsequently, the relationship between the two was calculated, giving the final score in% that depended on the score obtained Table 1.

TABLE 1. Evaluation of the Factory Maintenance System

From 90 to 100%	Excellent
From 80 to 89.9%	Good
From70 to 79.9%	Regular
From 60 to 69.9%	Bad
Less than 60%	Appalling

Analysis of the History of Faults that Have Occurred in the Pumping Equipment

To analyze the history of the faults, the pump logs were reviewed, with the pumping hours of each and the fault reports made by the pump operators. Once the logs were reviewed, the faults presented were classified according to the characteristics of the faults in electrical or mechanical faults. Mechanical failures represented a high percentage in the total number of failures. They included all types of manufacturing malfunction and effort fatigue. Once the faults that occurred in mechanical or electrical were classified, the causes of each one were analyzed, taking into account the revised documentation, the manufacturer's manuals and the results obtained in the technical and maintenance diagnosis.

The pertinent recommendations were then made to reduce the causes of the failures presented.

RESULTS OBTAINED

Criticality Analysis to Detect the Company with the Greatest Failures

The participants in the criticality analysis were all (5) Main Specialists of Technology and

Production and Mechanical and Electrical Engineers with more than 10 years of experience.

The results obtained for the indicators with the greatest impact are shown below:

- The frequency of failure obtained from the analysis of the companies' records showed a total of failures due to breakdowns during the period 2012 to 2016, up to 24, of which 12 were mechanical breakdowns and 12 were electrical breakdowns. On the other hand, it is observed that in the company Cultisur, 11 failures occurred for 48% of the total and, in the company Calisur, there were 8 failures, for 35% of the total occurred.

In all cases, these abnormal behaviors of the electrical or mechanical components prevented the correct operation of the pumps.

- The production levels (NP) were obtained from the statistical records of the Production Direction of the Companies, being able to verify in them that, in the period analyzed, a total production of 21009.10 ton was obtained. The most significant company was Calisur, which contributes 41% of the production, followed by Cultisur, which contributes 28% of the total production of the period analyzed.

- The environmental impact (IA) considered the possibility of alterations to the environment caused by the breakdowns that occurred. Of all the pumps installed, only 3 have diesel engines, which could be a source of environmental contamination in case of failure.

- Equipment replacement costs (CE) were obtained from the statistics of the investment process. During the 2012-2016 period, 25 pumping equipment was replaced by investment. Of them, 22 electric pumps and 3 diesel motor pumps.

- Finally, the repair costs (CR) associated with the failures were extracted from the balance sheets and work orders. If a quantitative analysis is carried out, it can be seen that they represent 4% of the total acquisition value of the pumps.

With the data obtained and the guide, the following table of criticalities was obtained (Table 2):

TABLE 2. Results of the criticality calculation

UEB	FF	NP	CE	CR	IA	Criticidad
Cultizaza	1	6	4	5		15
Cultisur	6	9	6	25	35	450
Sanros	1	4	2	3		9
Guajaca	1	4	1			5
Calisur	4	12	6	25	35	312

Preliminary Conclusion

Two UEBs that are considered most critical for the productive process are highlighted, the UEB Cultisur and the UEB Calisur. Therefore, the technical and maintenance diagnosis, as well as the analysis of the faults that occurred to the water pumps, was carried out in those companies.

Technical Diagnosis

Electrical Measurements

Behavior of Nominal Currents in Station 1 of Cultisur.

The average voltages behave above the nominal value recommended by the manufacturer, which is 460 ± 5%, that is, maximum 483 VAC, and they are outside the margins established, according to Cuban standard NC 365: 2009.

Results Obtained in Stations 2 and 3 of UEB Cultisur

In these pumping stations the voltage fell to levels that are in the limit below the value recommended by the manufacturer 460 ± 5%, in this case 437 VAC. This happened when more than three pumps were connected in the two pumping stations, which increased the consumption of the transformers and caused the voltage drop. There was no imbalance between the phases.

UEB Calisur.

In this pumping station, the level of phase 2 was out of phase with respect to the other two.

Equation 2 was used, obtaining the following imbalance:

$$Porcentaje\ de\ desbalance = [(448 - 437)/448] \times 100\% = 2{,}46\%$$

The minimum values were taken

V1 = 406 V

V2 = 384 V

V1 - V2 = 22 V equal to 6% of V2

So it can be said that in this pumping station there is a phase imbalance greater than that allowed by the regulations in force. The reason is that one of the high voltage lines of the three-phase system was connected to the single-phase network of a town located in the perimeter area of the pumping station.

It was appreciated that both the UEB Calisur and Cultisur incurred payments for penalties for low power factor during the years 2014 to 2016.

Analysis of the Eccentricity and Permanent Deformation of the Axes

Measurements were made using the case clock and the caliper gauge, obtaining in all cases values within the ranges established by the manufacturer.

Preliminary Conclusions

In both UEB there is poor quality of energy and some of the ETEC pumps present vibratory phenomena in the order from moderate to very strong due to poor conditions of the civil structure where they are installed and non-compliance with the manufacturer's recommendations regarding anchoring and protection against garbage and objects that may arise in the suction of pumps.

When checking the eccentricity of the axes, it was found that they do not have deformations or flexures that compromise the proper functioning of the pumps. In the case of the alignment between the motor axes and the axes of the pump, at the time of the measurements had been corrected, by recommendations of the authors, and they were within the ranges established by the manufacturer.

Vibration Measurement

The following preliminary conclusions were drawn from the analysis made of the data obtained:

- In Station 1, at Cultisur, the vibrations shown indicate a little strong and very strong levels in the pumps that have horizontal electric motor. The fundamental cause, which stands out from the visual inspection carried out, is the state of the flexible couplings. In the case of the pump that showed very strong VI scale vibration levels, the flexible coupling was totally deteriorated.

- In the case of the third pump of Pump Station 1, whose measurement showed a moderate level of vibrations, the cause was because this pump had recently been installed in a pit where there was sediment accumulation without the previous cleaning established. Once the pump worked for 24 hours, the measurement was made again and it was found that, the level of vibrations decreased to the category of mild.

- In none of the three pumping stations, there was filtering mesh at the entrance of the stations, which is why the garbage circulating in the supply channels reach the pumps causing obstructions, vibrations and mechanical damage.

- In UEB Calisur, the vibration of the pump in Station 1 was perceived as a little strong due to the presence of sediments in the pit where the pump was installed. In this case, the pump could not be operated until the pit was cleaned and measured again, due to the electrical problems described in the previous section.

- In Station 2 of UEB Calisur, vibration levels were observed in the VI scale of the digital vibrometer. The cause that derives from the visual inspection for this case is the bad constructive conditions of the station itself.

- In Pump Station 3, the vibrometer recorded vibrations in the order of moderate to a little strong; the cause of this level of vibration was the fact that the pumps were not anchored as recommended by the manufacturer.

Maintenance Diagnosis

6 pumping stations of the two UEBs were surveyed and evaluated.

When visiting the pumping stations of Calisur and Cultisur it was possible to observe the state of constructive deterioration. The poor condition of the Calisur pumping station 2 is relevant, where corrosion and lack of maintenance caused the loss of the cement cover and exposure to nitrate of the steel of the structures or piles.

In addition, during the tour of Cultisur stations it was possible to observe the poor state of the electrical distribution channels, which are at the level of the road where tractors and carts circulate and are continuously filled with mud, stones, vegetation, etc. with the consequent interment and deterioration of the electric cables.

Another important aspect observed in UEB Calisur was that the anchoring of the pumps in stations 2 and 3 was not carried out according to the manufacturer's design.

In UEB Cultisur, it was observed that the pumping stations do not have filters or garbage containment meshes at the entrance of the stations. These meshes should be placed in the channel so that garbage is contained in one place before the water reaches the pumps. When the channel does not have grids, the garbage reaches the pumps and over time, they obstruct its control grid with serious consequences for its operation.

Finally, during the tours and the visual inspection, it was observed that some of the discharge boxes of the pumping stations, both Calisur and Cultisur, are too high, with a level above the discharge pipe, which causes an overconsumption of current in the pumps and therefore energy inefficiency.

Economic Evaluation

To carry out the economic evaluation, three fundamental results were taken:

Cost of repairs for unforeseen breakdowns.

The repair cost of the breakdowns amounted to 105,318.06 pesos in repairing faults that constitute approximately 4% of the total acquisition value of all the pumps. Of these, 39,800 CUP correspond to repair of faults due to mechanical failures. From the diagnoses made and from the analysis of the causes of failures, it was concluded that the manufacturer's recommendations were not met and the frequencies of the preventive maintenance were violated, which would have prevented the occurrence of the failures and, therefore, the repair cost. The negative effect is also given in the fact that the pumps suffered considerable mechanical damage when their acquisition value has not yet been amortized, which leads to an increase in the cost of the asset.

Analysis of the power factor.

From the analysis of the power factor carried out, it could be seen that both UEB Calisur and Cultisur paid penalties for low power factor in their pumping stations. This situation is reversed in 2017 since the importation of 50 kV capacitor banks was carried out at the end of 2016 and they were installed in the pumping stations that are still enabled. On the other hand, the supplier was requested that the control boards of the last nine imported pumps had the capacitor bank incorporated to compensate for the inductive load. The result shows that it was feasible to buy the capacitors and the boards, since the total expense was lower by 46 065.51 pesos equivalent to what was paid by penalty in the last three years and a bonus of 15,000 CUD was observed immediately the changes have been made.

Economic evaluation of the discharge drawer.

As revealed during the visual inspection, the discharge boxes cause inefficiency in the pumping due to the height that the pumps must overcome in order to pour the liquid into the reservoir. During the electrical measurements, it was possible to verify that the pumps associated to an entire drawer of discharge consumed 20 A more than the pumps whose drawer was already modified. Based on this result, taking as a value of payment per kW to the electric company in force, it is concluded that approximately 5,896.00 CUP per month can be saved if the modification to the rest of the unloading drawers of the UEB analyzed were made.

CONCLUSIONS

- With the accomplishment of this work, the general objective was fulfilled, since the causes of the failures presented in the axial electric pumps were identified and recommendations were made to achieve their reduction.
- It was determined that the causes of the mechanical failures that occurred in the axial electric pumps are due to the lack of organized maintenance, efficient and developed on the basis of a competitive cost, which will guarantee the functionality of them. In the case of electrical faults, the fundamental cause was the poor quality of the supply energy.
- Twenty-one recommendations were made for the reduction or elimination of the 35 determined faults.
- The economic analysis showed that, if the preventive maintenance and the manufacturer's recommendations had been executed, an approximate of 105,300.00 pesos in repairing faults, that constitute approximately 4% of the

total acquisition value of all the bombs, would have been saved. Also in the economic analysis, it is clear that, if the recommended modifications were made to the unloading boxes, the company would save at about 5,896.80 pesos monthly.

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