UNIVERSITAT POLITÈCNICA DE CATALUNYA
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Escola d'Enginyeria de Barcelona Est

FINAL DEGREE THESIS

Mechanical Engineering

Implementation of a wireless monitoring system for a centrifugal pump

Memory – Budget – Annexes

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RESUM

L'objectiu d'aquest informe és seleccionar, configurar i determinar els punts d'instal·lació d'un sistema d'adquisició de vibracions totalment sense fil per tal de monitoritzar en línia una bomba centrífuga situada en una estació d'Aigües de Barcelona. El monitoratge sense fil d'una bomba centrífuga implica una minimització de costos a l'hora de desenvolupar la instal·lació i major flexibilitat en la recolecta de dades, reduint el risc de danys i d'interferències electromagnètiques.

Es proporcionen explicacions detallades del camp de les vibracions aplicat a les bombes centrífugues, inclòs l'equip necessari per al seu correcte seguiment. La recerca per a la selecció d'instrumentació, el procediment de configuració i l'elecció dels punts d'instal·lació són els objectius principals d'aquest document. A més, s'ha realitzat una anàlisi comparativa entre diferents terminals d'Aigües de Barcelona amb la finalitat de facilitar el futur diagnòstic i manteniment de la bomba centrífuga sotmesa als objectius del projecte.

RESUMEN

El presente informe tiene como objetivo seleccionar, configurar y determinar los puntos de instalación de un sistema de adquisición de vibraciones totalmente inalámbrico para la monitorización online de una bomba centrífuga ubicada en una estación de Aigües de Barcelona. El monitoreo inalámbrico de una bomba centrífuga implica una minimización de costes a la hora de llevar a cabo la instalación y mayor flexibilidad en la recolecta de datos, reduciendo el riesgo de daños y de interferencias electromagnéticas.

Se proporcionan explicaciones detalladas del campo de las vibraciones aplicado a bombas centrífugas, incluyendo el equipo necesario para su correcto monitoreo. La investigación para la selección de la instrumentación, el procedimiento de configuración y la elección de los puntos de instalación son los principales objetivos de este documento. Además, se ha realizado un análisis comparativo entre diferentes terminales de Aigües de Barcelona con el fin de facilitar el diagnóstico y mantenimiento futuro de la bomba centrífuga objeto de los objetivos del proyecto.

ABSTRACT

This report objective is to select, configure and determine the installation points of a fully wireless vibration acquisition system in order to online monitor a centrifugal pump located in an Aigües de Barcelona station. Wirelessly monitoring a centrifugal pump implies the cost minimization of the installation procedures and more flexibility in the data collection, reducing damage risks and electromagnetic interferences.

Detailed explanations of the vibratory background in centrifugal pumps are provided, including the necessary equipment for their proper monitoring. The research for the instrumentation selection, the configuration procedure, and the installation points choice are the main purposes of this document. Furthermore, a comparative analysis between different Aigües de Barcelona terminals has been carried out with the purpose of facilitating the future diagnosis and maintenance of the centrifugal pump subjected to the project objectives.

ACKNOWLEDGEMENTS

Firstly, I would like to thank the director of this project, Mònica Egusquiza, for giving me the opportunity to learn about this new field and participate in such an interesting project. Without her advice and management it would not have been possible to carry out this project.

I would also like to thank my parents and my sister for the unconditional support they have given me throughout my studies.

GLOSSARY

Term:	**Meaning:**
Gateway	*Device used to connect diverse networks*
Acoem EAGLE	*Acoem accelerometer*
EAGLE EDGE	*Acoem EAGLE gateway*
OneProd Interface	*Configuration interface provided by Acoem to configure their accelerometers and gateways*
OneProd Cloud	*OneProd monitoring website and data-base*
OneProd Tree	*OneProd cloud and interface tabs distribution*
SG Set	*Centrifugal Pump specific set belonging to Aigües de Barcelona*
Station / Terminal	*Locations of the pumps sets*
FFT	*Fast Fourier Transform*
DFT	*Discrete Fourier Transform*
Peak / Crest	*Highest point of a curve or diagram*
Spectrum	*Values of a diagram classification between two points*
RMS	*Root Mean Square*
MQTT	*Messaging protocol used for the communication between machines*
Modbus channel	*MQTT channel to connect the OneProd interface and cloud*
Frequency Filters	*Determined bandwidth frequency spectrum*

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1. INTRODUCTION

A centrifugal pump is a mechanical device destined to transport fluids by converting mechanical energy into kinetic and pressure energy. Centrifugal pumps are essential to guaranteeing the adequate and continuous supply of liquids in various operations, optimizing fluid transport systems, reducing pressure losses, and minimizing energy consumption.

Given the importance of these machines, the implementation of vibration monitoring strategies is essential for them to operate in the best possible condition. There are various methods used to assess the status of centrifugal pumps; however, predictive maintenance has become the most widely implemented approach due to its wide range of applications and the efficiency it presents.

The choice of a predictive maintenance model is based on the ability to detect and predict potential failures or damages before they occur through uninterrupted monitoring. This allows preventive measures to be taken and maintenance activities to be planned more efficiently, minimizing unplanned downtime and reducing additional costs related to emergency repairs.

Offline monitoring used to be the most commonly applied technique for determining centrifugal pump condition. By measuring the vibration on-site using portable collectors, the information used to be transferred to a database for further analysis. Nowadays, there exist more advanced methods consisting of online collection. However, installing the wired acquisition equipment is a complex process that could be expensive and delicate. As a consequence, the wireless systems importance has grown, reducing installation costs and obtaining more accurate information from the sensors.

One of the main advantages of implementing a fully wireless and online monitoring system is the ability to monitor the condition of the pump in real time, without interruptions or cables limiting flexibility and accessibility. This facilitates the early detection of any change or anomaly in the vibrations of the pump, allowing the optimization of resources and the maximization of operating efficiency. By reducing response time and minimizing costs associated with maintenance, companies can ensure the reliable operation of their pumping systems, guaranteeing customer satisfaction and long-term profitability.

This report focuses on the selection and configuration of wireless vibration monitoring equipment for a centrifugal pump located in an Aigües de Barcelona station, with the aim of implementing a wireless vibration monitoring.

1.1. Project goals and scope

This report is focused on the implementation of an online monitoring model in an Aigües de Barcelona centrifugal pump by selecting, configuring and determining the installation points of a fully wireless vibration acquisition system.

With the purpose of fulfilling these objectives, the first step is to comprehend how condition monitoring systems operate. Researching vibration monitoring and working principles applied to turbomachinery has been fundamental for the development of this document.

In order to complete the equipment configuration, it has been necessary to search among the multiple suppliers for a wireless monitoring system that perfectly fits with the centrifugal pump under study necessities. Performing the proper configuration of the instrumentation and installing it on the appropriate points of the machine is fundamental for the implementation of this report.

The project finds its basis in a specific centrifugal pump belonging to Aigües de Barcelona, installed at the *G3 SG II* terminal. This document has been prepared to, in the near future, install and wirelessly monitor the vibration of pumps in the *G3* station, determine the machines condition, and highlight why wireless transductors, nowadays, belong to a sensor type that prevails over other systems with similar uses.

1.2. Methodology of the project

Intending to fulfill the objectives of this document, it has been necessary to establish a specific methodology.

Firstly, it has been required to comprehend how centrifugal pumps operate, including their working principles, their functions, and the existing types. Their unique operating manners are prone to generating internal vibrations that may affect their integrity. Therefore, vibration principles and sources in turbomachinery have been studied in detail in order to understand the importance of their consequences.

Research for vibration monitoring has been a fundamental step to satisfy the purposes established. Understanding the requirements of a monitoring system and its operation is paramount to learning about the necessary equipment. Searching for the best instrumentation by taking into account the demanding predictive maintenance strategy requisites has become an obligation for differentiating between wired and wireless transductors. Furthermore, considering the best parameters to study with the chosen acquisition system and adapting them to the data collection procedure has been conditioned by the theoretical background built into this manuscript.

The project developed considers the own characteristics of the pump set under study, adapting the vibration acquisition system configuration to the machine requirements. Detailed explanations of the vibratory analysis procedure, the defect detection, and the fault diagnosis are provided in this report with the purpose of selecting the equipment, configuring it and representing the possible diagnosis of a *G3 SG II* centrifugal pump.

In search of the completion of the objectives stated in this document, a comparative analysis between other stations monitoring condition results has been performed, evaluating the specific defects suffered by the centrifugal pumps installed at other terminals.

The comparison between stations is centered on deducing the future defects and possible diagnosis of the *G3 SG II* center. The other terminals, pertaining to the *SG* set, have previously been subjected to continuous monitoring, giving access to a condition database utilized to conduct the comparison.

The resulting report provides detailed explanations of how a wireless vibration acquisition system has been effectively selected and configured, considering the specific characteristics of a centrifugal pump and determining the fundamental points where the collectors must be installed. By approximating the installation potential faults, it is possible to ensure adequate monitoring and predictive maintenance of the machine, optimizing its performance and prolonging its useful life.

2. CENTRIFUGAL PUMPS

A turbomachine is a machine type whose function is to transfer energy between a fluid and a rotor. The energy transfer can be in the form of pressure, velocity or a combination of both. There are four classes of turbomachines:

- Turbines: This type of equipment harnesses energy from a fluid and converts it into rotational energy for powering mechanical systems. These machines are primarily designed for electricity generation and propelling aircraft.

- Compressors: These machines increase the pressure of a gas by adding kinetic energy to the airflow. They find their applications in air conditioning systems and industrial processes.

- Fans: This group transfers energy to a gas in order to move a large volume of it. They are commonly used in cooling towers and ventilation systems.

- Pumps: Centrifugal pumps transfer liquids from one point to another by increasing the velocity and pressure of the fluid.

A centrifugal pump is a rotodynamic hydraulic machine capable of converting mechanical energy into hydraulic energy. It transfers energy to the fluid by generating centrifugal force due to its own rotation, increasing the pressure. The main components of a pump are:

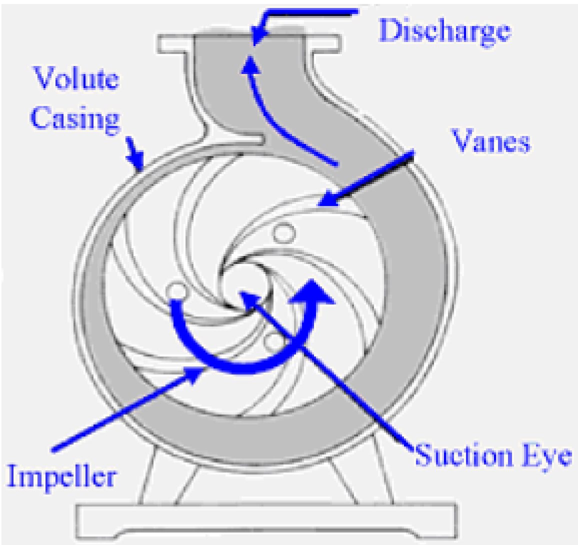


Figure 2.1. Front view of the fundamental parts of a pump [1]

- Impeller: It is a large metal disk with blades on its projections. Its function is to propel the fluid and transfer to it the energy of the rotor, accelerating it towards the edges of the disk.

- Casing: The external and protective part of the pump, which aims to reduce the fluid velocity depending on its area, which gradually increases in the form of a cone.

- Shaft: Transmits the rotation of the rotor throughout the pump, supporting and aligning all the components of the machine.

- Wear rings: Affordable components that are strategically placed in areas where friction is expected, with the purpose of safeguarding the impeller and the shaft. Replacement of these components is done when it is required.

- Bearings: Composed by two concentric cylinders separated by a ball bearing, these devices reduce stress and friction between the shaft and the components it connects with, facilitating the rotation of mobile elements.

- Mechanical seal: It acts as a containment system, isolating the pumped fluid.

Centrifugal pumps enable the connection between some hydraulic installations, facilitating a solution to the lack of pressure at certain points, where there is a high level difference and fluid pumping is required, working as an elevator.

2.1. Working principles

A centrifugal pump consists of an impeller that rotates inside the machine, transferring kinetic energy to the fluid, which is pumped through the impeller blades. Externally, it is surrounded by a protective casing and equipped with suction and discharge nozzles. The suction nozzle is on the axis of rotation of the impeller while the discharge nozzle is perpendicular to the horizontal axis.

The liquid pumped enters the impeller from the suction nozzle and it is accelerated by the blades to the disk edges, where it is discharged into the casing. The acceleration the flow is subjected to is due to the thrust force provided by the helical blades of the impeller, gaining kinetic energy and, once the fluid enters the casing, it decelerates.

The deceleration speed depends on the casing shape, the more the section expands the more the fluid decelerates. The section increase between the impeller and the casing is influenced by the size of the nozzles installed because, relying on the type of nozzle and its opening, the shape of the blades must be different [2].

In order to evaluate the behavior of a centrifugal pump, the characteristic curves of the machine must be understood. The characteristic curves are representations of multiple pump operating conditions indicators, being crucial when evaluating the functioning status of the machine. The main characteristic curves when analyzing a running centrifugal pump are:

1. Head-Flow Curve: The QH-curve illustrates the relation between the head and the flow rate, displaying the head the centrifugal pump is able to perform at a given flow volume.

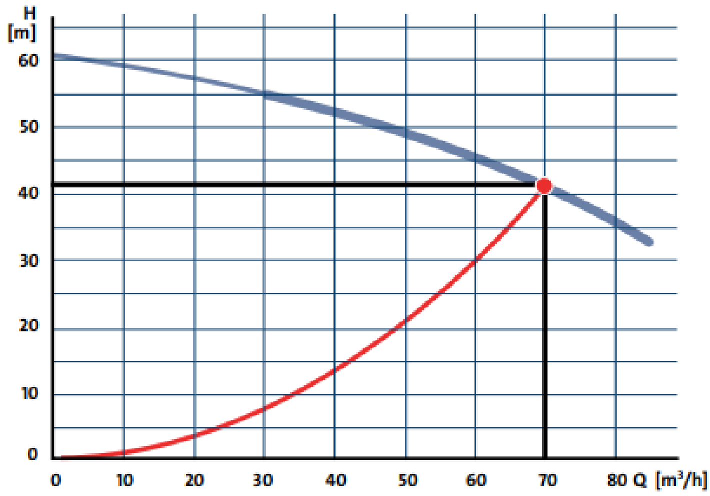


Figure 2.1.1. QH-Curve of a pump [3]

For the purpose of tracing the QH-Curve the following equation is calculated:

$$H = H_{static} + \frac{Q^2 * f}{2g * A^2} \quad \textbf{(Eq. 2.1.1.)}$$

Where "H" is the head the pump is able to generate in meters, "H_{static}" is the distance from the pump center to the discharge nozzle in meters, "Q" is the flow rate passing through the pump in m^3/s, "f" is the fluid-surface friction factor which is adimensional, "g" is the gravity acceleration in m/s^2 and "A" is the section of the tube in m^2.

As it can be appreciated, the lowest flow volume results are obtained in the highest heads, a logical result attributable to the casing deceleration factor. As previously commented, the casing has a cone shape that increases its section, permitting the fluid to decelerate when entering into it. Observing the equation and the QH plot, the larger the section becomes, the lower the head gets, resulting in a faster flow rate.

2. Efficiency-Flow Curve: The η-curve illustrates the relation between the power supplied and the power actually utilized. When applied to a centrifugal pump, efficiency refers to the relation between the power delivered by the pump to the fluid and the input to the shaft.

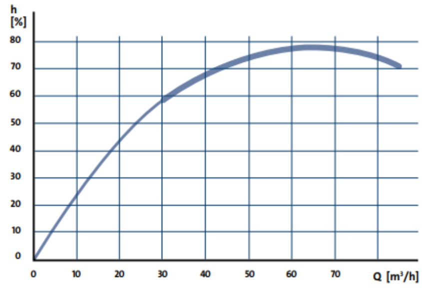


Figure 2.1.2. Efficiency curve of a pump [3]

In order to represent this curve, the following expression is required:

$$\eta = \frac{P_H}{P_S} = \frac{\rho * g * Q * H}{P_S * 3600} \qquad \textbf{(Eq. 2.1.2.)}$$

Where "η" is the total efficiency as a %, "P_H" is the hydraulic power in horsepower or Watts, "P_S" is the power input to the shaft in horsepower or Watts and "ρ" is the fluid density in kg/m^3. In the event the fluid is water at 20°C, the resulting "P_H" is:

$$P_H = 2,72 * Q * H \qquad \textbf{(Eq. 2.1.3.)}$$

3. Power-Flow Curve: The PS-curve illustrates the relation between the power consumed by the pump and the flow volume. It shows how the power consumption varies with changes in flow rate and, in the majority of the cases, increases as the flow grows.

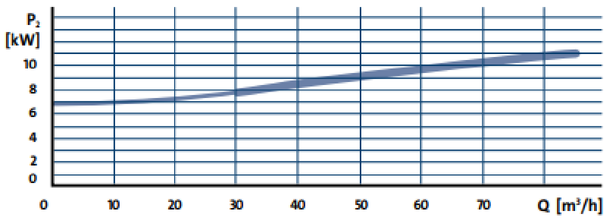


Figure 2.1.3. PS-Curve of a pump [3]

The PS equation is the same that describes the efficiency curve:

$$P_S = \frac{\rho * g * Q * H}{\eta * 3600} \qquad \textbf{(Eq. 2.1.4.)}$$

4. Net Positive Suction Head (NPSH)-Flow Curve: The NPSH-curve illustrates the relation between the NPSH the pump requires and the flow rate passing through it. The NPSH is the minimum suction absolute pressure needed when intending to avoid cavitation.

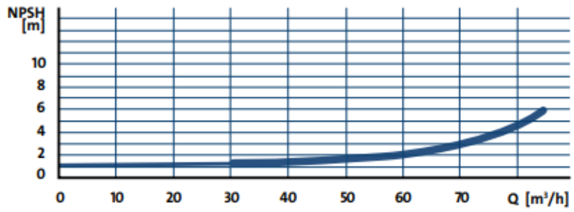


Figure 2.1.4. NPSH-Curve of a pump [3]

As it can be observed, when the flow volume increases, the NPSH-value also grows. This curve is typically facilitated by the manufacturer but there is an expression that can be applied when studying cavitation origins, the required NPSH (NPSHR) in m:

$$NPSHR = \frac{P_{vap} - P_{d} - H_{f}}{\rho} \qquad \textbf{(Eq. 2.1.5.)}$$

Where “P_{vap}” is the vapor pressure of the fluid in Pascals, “P_{d}” is the discharge pressure in Pascals and “H_{f}” are head friction losses in meters.

5. Specific Speed-Efficiency Curve: The nq-curve represents the relation between the pump specific speed and the efficiency of the machine. It is understood as specific speed the amount of revolutions the pump must execute in order to propel the flow rate to a head of one meter.

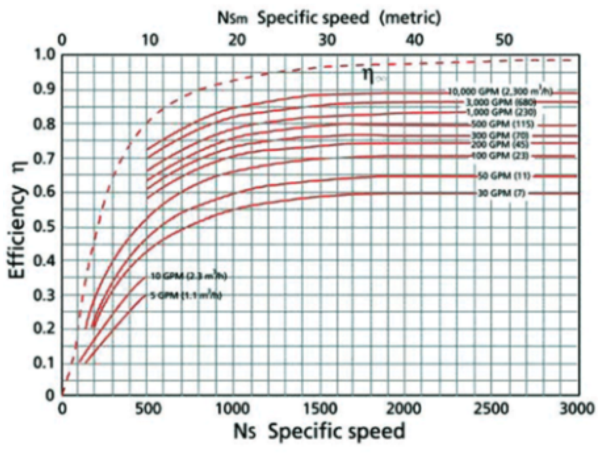


Figure 2.1.5. Specific speed curve of a pump [4]

This parameter can also be plotted in contrast to the flow rate, but it is frequently compared to the pump efficiency because it is easier and implies the same results. The specific speed is calculated as:

$$n_q = n * \frac{Q^{1/2}}{H^{3/4}} \quad \textbf{(Eq. 2.1.6.)}$$

Where "n_q" is the number of laps and "n" is the rotational speed regime in rpm.

Once the five characteristic curves of a centrifugal pump are taken into account it is possible to simulate and understand the operating conditions of the machine.

2.2. Types of centrifugal pumps

There are three types of centrifugal pumps with specific functionalities and objectives determined by their characteristics and capabilities. The most frequent types, depending on the impeller collocation and installation, are the following [5]:

- Closed impeller: The impeller is compressed between two rotating disks in a single frame. It is used in large pumps with high efficiency. They require a positive suction nozzle, which implies a suction greater than the generated pressure. They are complex but widely used when working with transparent fluids.

- Open impeller: Delimited by one rotating disk, the edges of the impeller blades must be at a certain distance from the casing to create freedom in movement. They are used when working with smaller pumps, handling suspended solids.

- Vortex impeller: Installed when the fluid being handled may contain sand or other debris, they allow for flow with minimized obstructions. As it rotates, it generates a vortex under the surface of the moving fluid.

Centrifugal pumps can also be classified in function of the main parameters of the machine:

- Number of impellers: Centrifugal pumps can be single-staged, implying that there is only one impeller pumping the fluid, or multi-staged, meaning that more impellers are fitted in series. Multi-stage pumps are determined by the type of impeller and the rotational speed.

- Orientation of the shaft: Horizontal pumps are one of the most widely used models with industrial purposes, having the shaft parallel to the ground means that they are easier to maintain and install. On the other hand, vertical pumps are designed to lift fluids from high depth and pump them at higher pressures.

- Space: There are different types in function of the space restriction the installation must follow, depending on the shape of the casing and the shaft length, among other parameters.

In order to choose the most appropriate pump for each installation, focusing on its main qualities, the object under study are the specific characteristics of the centrifugal pump.:

- Impulse and shaft: The pumping rotational power of the impeller and its affinity with various fluids combined with the positioning of the shaft determine the functional qualities.

- Casing, cover, and supports: Depending on the resistance, endurance, and positioning of the structural parts of the machine, the impact on the maintenance of the bomb varies. These parameters directly affect both the accessibility to replacement areas and the frequency of requiring this treatment.

2.3. Applications

Centrifugal pumps transform mechanical energy into hydraulic, transferring this energy generation to the incompressible fluid it transports inside. The pressure contribution provided by the pump is the reason why its field of work has mainly been the transportation of fluids in points where greater energy is required. Since the fluid is pumped, it accelerates, allowing the machine to move the liquid from a low potential point to a higher altitude.

In addition to their function as an elevator, it is very common for them to complement other hydraulic installations in a wide variety of sectors. Some of the most prominent applications of these complex turbomachine are:

1. Industrial: Transportation of fluids within any industrial sector, prioritizing chemical and cosmetic industry.
2. Automotive: Fluid treatment, conveyor belt and hydraulic assistance.
3. Food industry: Transferring fluids such as sauces and juices, among others.
4. Commercial and residential buildings: Distributor of water and/or ventilation.
5. Fire protection: In the event that smoke detectors go off in a building, a pump propels water as a method of protection for civilians.
6. Agriculture: Crop irrigation and distribution of fertilizers.
7. Mining: Transportation of sludge, wastewater, and other fluids.
8. Power generation: Circulation of water and steam in power plants.
9. Water treatment: Water purification, and water treatment.
10. Oil and natural gas industries: Transportation of oil and natural gas.

3. VIBRATION IN CENTRIFUGAL PUMPS

The propagation of mechanical energy waves through a material around an equilibrium position is the phenomena known as vibration. The sinusoidal waves produced by vibrations are characterized by the amplitude, frequency, and wavelength presented, which are fundamental in order to determine the origins of this movement.

Vibration is a high-frequency periodic motion, which can generate noise and fatigue in the transmitting element of the movement. It is a natural phenomenon that takes place in almost all machines and, in fact, vibrations do not usually imply a flaw in the machine. For this reason, vibration analysis is used in the study of the condition of centrifugal pumps since if unusual vibrations are perceived, it could be due to an origin that could be identified through this method.

As a result of multiple processes, noise is produced and, depending on how it is transported, it can be divided into two groups. The first origin of the noise is a result of vibrating elements of the machine that, when colliding with other parts, generate sound. On the other hand, the second origin propagates the noise through the air, generating acoustic radiation. This sound can be decisive in determining the equipment status since it could be caused by an emerging problem.

3.1. Vibration principles and waveform definition

Vibrations are produced when the equilibrium of a system is disturbed. When related to turbomachines, a system refers to interconnected parts that can be displaced or deformed. Equilibrium implies a force balance, meaning that the shaft must be rotating at constant velocity so, if the balance is broken, it is because of a rising force. In case of the appearance of an incipient influence that exceeds the flexibility limits of the system, the equilibrium will be disrupted.

The part subjected to this force will experience a displacement corresponding to the impact magnitude and, if it surpasses the flexibility threshold, the structure may fluctuate around its resting position resulting in vibrations. The vibrations dimensions will vary in function of the amplitude and frequency of the force and the damping qualities of the structure. When the influence is applied with a similar frequency to the one that allows the body to oscillate with no restrictions, or natural frequency, it may cause resonance.

In order to regulate the incipient abnormal vibrations, it is required to consider the principles that govern these occurrences. Vibration waves have the capability to combine and overlap with each other implying that if multiple waves come into resonance, they will merge resulting in a superimposed amplitude with more severe consequences.

Vibratory waves are described by the forces that generates them and their shapes:

1. Vibration principles: There exist three main forces that generate vibrations.
   - Hydraulic forces: The hydraulic force appears when a fluid exerts pressure on a contact surface. Once the impeller blades propel the fluid, the contact triggers an emerging increase of pressure. These forces vary in direction depending on the flow rate and the fluid velocity, generating unsteady stresses deriving in vibrations.
   - Mechanical forces: The mechanical force appears when an element is subjected to loads. Bearings, the motor and shafts are some parts prone to suffer from mechanical efforts such as friction, compression and torsion. In a centrifugal pump the forces applied to these components is usually due to the rotation of the system and the own function of each element.
   - Electrical forces: The rotation that generates both mechanical and hydraulic forces is produced by an electric motor that powers the internal movement.

   The most frequent vibration sources are the effects produced by the mechanical forces:

   a) Inertia: It refers to the tendency of an element to change its movement status, for example, the impellers rotating and pressing the fluid. This can result in components wear and, therefore, vibrations.

   b) Friction: The continuous contact between two components means an increase in the temperature range of those parts, provoking an efficiency loss, noise and vibrations.

   c) Elastic tension: The elastic deformations of some parts such as the shaft, the impeller or even the motor are accumulative, implying that, if this tension does not disappear, the components can generate vibrations and, in the worst cases, fractures.

   Knowing the forces that may disturb the system equilibrium, it is possible to describe a stability equation based on those forces. The following expression is The Second Newton's Law applied to the impeller circumstances, that include the friction with the fluid, the centrifugal force of the rotation and the elastic force suffered by the impeller [6]:

$$\sum \overline{F} = m * \overline{a}$$

$$\overline{F}_c - \overline{F}_e - \overline{F}_f = m * \overline{a} \qquad \textbf{(Eq. 3.1.1.)}$$

   Where "F_c" is the centrifugal force, "F_e" is the elastic force and "F_f" is the friction force, all three forces represented in Newtons, "m" is the impeller mass in kilograms and "a" is the impeller acceleration in m/s.

It is also important to consider the forces own equations:

$$F_c = m * q * r \quad \textbf{(Eq. 3.1.2.)}$$

Where "$m * q * r$" is the mass flow rate in kg/s [7].

$$F_f = \mu * N \quad \textbf{(Eq. 3.1.3.)}$$

Where "μ" is the friction coefficient and "N" is the normal force of the surface-fluid contact in Newtons [8].

$$F_e = x * k \quad \textbf{(Eq. 3.1.4.)}$$

Where "k" is the impeller elastic constant in N/m and "x" is the displacement the impeller has deviated from its equilibrium position in meters [9].

When the forces the impeller is subjected to are described, it is possible to simplify The Second Newton's Law when applied to a centrifugal pump study:

$$\overline{F}_c - \overline{F}_e - \overline{F}_f = m * \overline{a} \quad \textbf{(Eq. 3.1.1.)}$$

$$m * q * r - \mu * N - x * k = m * \overline{a} \quad \textbf{(Eq. 3.1.5.)}$$

This equation represents the sum of the forces that produce the instability of an internal system, describing the operating condition of this machine.

2. Vibration waveform: Once described the origins and the principles of the vibrations, it is possible to adapt several equations to represent the vibratory waveform and perform a better interpretation of the vibration principles [10].

    - The Hooke's law establishes that the force required to compress or stretch a spring is directly proportional to its elongation:

$$F =- k\Delta x \quad \textbf{(Eq. 3.1.6.)}$$

    - The resonance equation allows the representation of the behavior of a wave when a periodic force is applied with similar frequency to the system natural frequency:

$$x = A * sin(\omega t) \quad \textbf{(Eq. 3.1.7.)}$$

    Where "A" is the maximum amplitude, "x" is the elongation at time "t", and "ω" is the angular frequency of the wave.

By deriving in first and second order , the following expressions are obtained:

$$v = A\omega * cos(\omega t) \qquad \textbf{(Eq. 3.1.8.)}$$

$$a = - A\omega^2 * sin(\omega t) \qquad \textbf{(Eq. 3.1.9.)}$$

Where "v" is the velocity and "a" is the wave acceleration.

- The simple harmonic equation represents the movement of a vibrating object around its equilibrium point:

$$x(t) = A * cos(\omega t + \varphi) \qquad \textbf{(Eq. 3.1.10.)}$$

Where "φ" is the initial angular position of the object and *"x(t)"* is the position of the object.

Similar to the resonance equation, by deriving the previous expression, the equation of the object velocity and acceleration are obtained:

$$v(t) = - A\omega * sin(\omega t + \varphi) \qquad \textbf{(Eq. 3.1.11.)}$$

$$a(t) = - A\omega^2 * cos(\omega t + \varphi) \qquad \textbf{(Eq. 3.1.12.)}$$

The wave equation allows to represent the sinusoidal oscillation of wave amplitude through a specific medium as a function of position at each instant of time:

$$y(x, t) = A * sin(kx - \omega t + \varphi) \qquad \textbf{(Eq. 3.1.13.)}$$

Where "y" is the wave amplitude and "k" is the wave number $(\frac{2\pi}{\lambda})$.

By understanding the forces that produce each vibratory wave and how their shapes are related to the signal characteristics, the vibration curve is totally defined.

3.2. Vibration sources in turbomachinery

Vibration can generate incessant movements that may lead to a negative effect on the behavior of the machine. The oscillating phenomenon is a natural reaction to the internal operations of a centrifugal pump but, in case of having an excessive force acting that exceeds the flexibility limits of the system and the interconnected parts can produce damaging vibrations.

There are various influential variables in the creation of internal vibrations in a centrifugal pump but the main sources of this unexpected behavior are [11]:

- Misalignment: Caused by the incorrect alignment of the rotation axis of the elements of the machine, it is one of the origins with the highest appearance factor. It is divided into three classes: parallel displacement, angular displacement, and angular and parallel displacement.

  This mismatch can create internal forces in the shafts, bearings and gears that may cause damage to these elements. The origins of this fact can be the deflection of the motor, asymmetric forces in the rotor and other types of overloads.

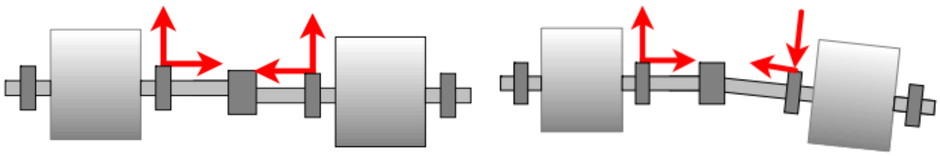


Figure 3.2.1. Parallel and angular misalignments in the shafts coupling [12]

- Unbalance: An uneven distribution of the rotating assembly around the axis of rotation, meaning a mass imbalance of the impeller, the shaft and other rotating parts. There always exists an unbalance because any machine is perfectly symmetrical.

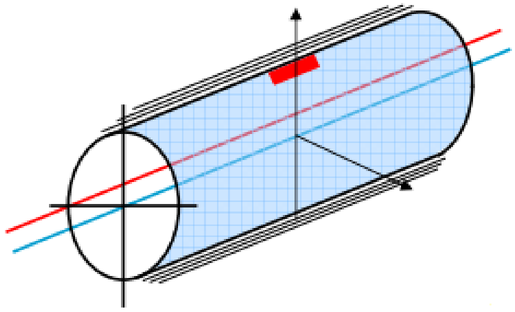


Figure 3.2.2. Static unbalance of the shaft [11]

- Resonance: Occurs when two or more elements of the machine vibrate synchronously, reinforcing the sound and increasing the vibrations amplitude.

- Periodic impacts: These impacts usually produce wave peaks when rotating and passing through load points, detected at each harmonic. Those load points can be internal to the machine, such as bearing and gear degradation, or external, such as fixing defects.

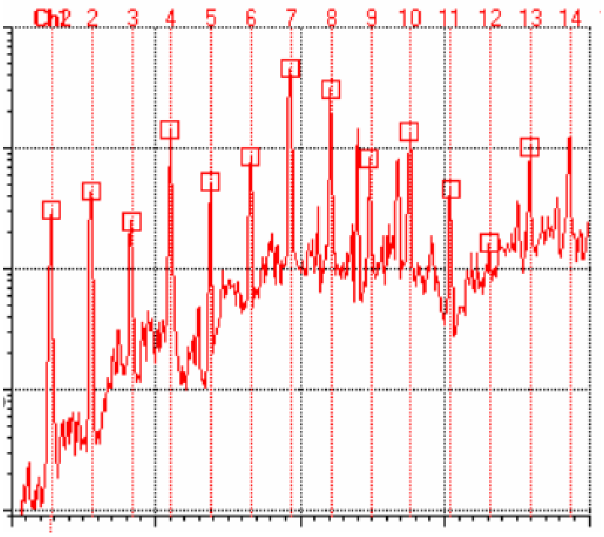


Figure 3.2.3. Periodic impacts due to bearing advanced misalignment [11]

- Defects related to the impeller: Due to friction, wear or profile damages caused by residues transported in the pumped liquid.

- Magnetic phenomena: They depend on the type of motor. Asynchronous AC motors cause defects due to the presence of magnetic fields. These fields can generate current variations and air gaps in the stator and rotor due to imperfections in those elements.

- Gears: Used in the transmission of engine torque, they frequently suffer imperfections in the gear profile and, when a tooth is damaged, periodic impacts occur.

  When teeth are degraded or broken, the backlash can become determinant in order to detect the vibrations origins. If the backlash between two gears is too soft, the second harmonic dominates and, on the other hand, if it is too hard, the registered harmonics have very similar amplitudes. If the tooth is damaged or broken, the result is very similar to hard backlashes.

- Drive Belts: Belt problems are often due to the misalignment of the shafts, which causes vibration. The parallel misalignment of this element can be the result of gear imperfections or a badly distributed force system.

- Bearings: Designed to reduce friction between rotating parts of the structure, they are exposed to a series of conditions that can cause damage to their profile, inducing them to chip at the surface and cause degradation.

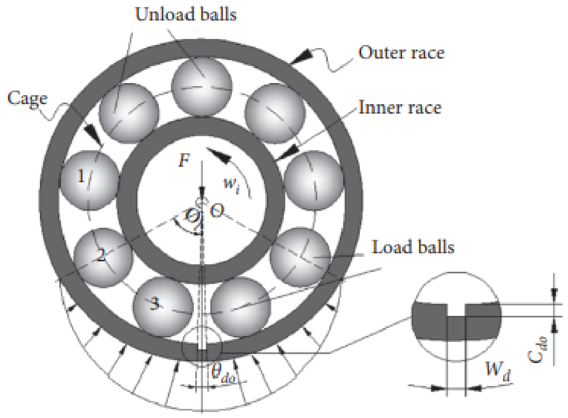


Figure 3.2.4. Bearing in load and unload zone [13]

- Hydrodynamic bearings: In this type of bearing, the shaft oscillates due to the oil film retained by the rotation. Shaft instability can occur due to rotor load, rotational speed, or oil viscosity resulting in an oscillating movement of the shaft.

Events that occur inside the turbomachines when the machinery is working are called phenomena. These phenomena include turbulence and cavitation, two of the most notable defects when referring to a centrifugal pump [14]:

- Turbulence is a disorderly movement of a fluid that creates small eddies that appear after overcoming the impeller. This event causes changes in the transported fluid speed and, as the velocity increases, the pressure on it decreases, creating vibrations.

- Conversely, part of the liquid in the pump evaporates and creates cavitation, small spaces filled with vapor in the form of air bubbles, which burst due to pressure variations. This generates vibrations similar to those produced by turbulent flow within the impeller.

4. VIBRATION MONITORING

Vibration analysis is a key technique in the diagnosis of rotating equipment that allows for the implementation of predictive maintenance programs to prevent future machine problems. Its functionality lies in monitoring the vibration of the pump for subsequent interpretation.

In order to prevent and detect serious consequences in the machine, more advanced techniques are combined with a mechanical methodology applying two different detection systems [15]:

- Detection of vibration offline: The vibration analysis parameters are measured on-site using portable vibration collectors, and the resulting data is transferred to a database for further analysis. However, this process requires specialized personnel stationed at specific locations, which can pose challenges in implementing the management system. Furthermore, by applying the senses, a phenomenon such as noise or vibration can be perceived.

- Online vibration and temperature measure: The vibration in the bearing, the shaft displacements, the temperature of the parts most susceptible to vibrations and the vibration frequency are studied with the aim of identifying the areas most vulnerable to excessive stress. This measure provides immediate data on the priority points that require attention.

- Continuous monitoring: Both aforementioned systems are applied in order to know the condition of the pump at regular intervals. This way, the machine is continuously monitored and immediate maintenance can be applied in case of diagnosing any defects.

Implementing a monitoring system through online tracking and periodic on-site inspections using portable collectors, enables the performance of vibration analysis in line with the predictive maintenance methodology, allowing for quick and accurate diagnosis of defects.

4.1. Predictive maintenance

Maintenance is understood as a process that guarantees the availability of the production at an optimal cost. It is possible to classify this process depending on the maintenance procedure [16]:

- Curative maintenance: This category focuses on responding to an error once the defect has appeared, implying a dyscontrol of the equipment availability. In the event of a breakage or a shutdown, an oversized maintenance team is required in order to solve the imperfection.

- Systematic maintenance: It replaces parts of the machine according to a predefined schedule, ignoring the actual condition of the equipment. Since this method proposes a preview of the machine condition, substitution parts are swiftly provided. Despite the planification and the rapid handover of the replacements, when an inesperate defect emerges, this system is unable to restrain the unexpected consequences.

- Conditional maintenance: It is a preventive procedure that focuses on a parameter related to the equipment degradation status. Whenever this parameter exceeds a pre-established limit, the reason for this alarm is studied in order to find a solution for the potential problem.

- Predictive maintenance: This system monitors the parameters related to the condition of the equipment before detecting any danger for the machine status. This method increases the equipment lifetime by anticipating any possible defect.

The predictive maintenance principles have their basis on the complete knowledge about the condition of the significant parameters related to the degradation status of the machine. These significant elements are parts subjected to efforts such as friction or strain and stress.

The main advantages of this method are associated with avoiding the production stops:

1. Decrease unplanned activities and unexpected stops.
2. Lessen operating costs.
3. Increase production disponibility.
4. Improve the safety of the equipment and the organization between maintenance operators.
5. Reduce on-site inspections and repairing costs.
6. Reduce inventory costs by delivering only the necessary parts.
7. Strengthen the work motivation and the quality.

The most used tools used in predictive maintenance are systems that aim to control the actual status of the installation. The four main means to prevent imperfections in a centrifugal pump are:

- Vibration monitoring: This technique compiles all data connected with internal vibrations in order to detect any unusual behavior of the equipment.

- Lubrication analysis: The objective of this parameter is to reduce the friction between the bearings and the shaft. This lubrication process is executed in series to prevent unnecessary over demanding efforts to the bearings.

- Thermography: By implementing this method, gradual temperature increases at the bearings and other rotative elements are revised. If the thermal image shows excessive growth, the origin of the undue friction is immediately studied.

- Process parameters monitoring: This technique is based on monitoring and controlling parameters such as temperature, pressure and flow, among others.

The process to follow when implementing a vibration monitoring system takes into account multiple factors, including economic preferences, accuracy of the results and the size of the installation monitored. As a result, every system is adapted to each installation needs:

1. Maintenance technique: The first step is to decide if it is more adequate for the installation to apply a preventive methodology or a corrective maintenance.

2. Implementation of a monitoring system: With the purpose of implementing a monitoring structure, it is necessary to understand the range the analysis and its characteristics:

   Referring to the system characteristics:

   - Safety: The machine must be designed to stop it in the event of risky working conditions for the equipment integrity. This may happen when the vibrations exceed the threshold the manufacturer has established.

   - Maintenance: Focusing on the prevention of irregularities from taking shape, a trend analysis is performed. Knowing the course of the vibration waves allows to deduce when and where a flaw could appear.

   - Monitoring systems: Depending on the regularity of the on-site data gathering and its accuracy, the qualities needed for the fixed and portable sensors are different. As commented before, when studying a centrifugal pump condition, there is an on-site periodic supervision and an online monitoring. The transductors fixed on the machine allow the uninterrupted online monitoring of the pump and, combining both online and offline systems, the knowledge of the status is fairly precise.

   The analysis range varies during the monitoring period in function of the results collected with the transductors:

   - Level 1 or entry range: When implementing a vibration monitoring it is fundamental to perform a trend analysis that remains throughout the entire tracking process.

   - Level 2 or advanced range: When unusual vibrations are perceived it is required to perform a diagnosis of the anomalies, that usually identifies the vibration origins.

- Level 3 or experienced range: Sometimes the root is not only one and vibrations derive from multiple sectors. In these cases, it is necessary to explore in more detail the possible causes of the unexpected vibrations.

3. Monitoring configuration: This implies the implementation of monitoring systems in a small number of facilities in order to reflect the indicators of production and the average status of a healthy pump. These factors vary depending on the number of pumps being monitored and the location of the measurement points in the machines. By controlling a reference amount of pumps, the average vibrations and their limits in a good condition machine can be defined and saved in the database to compare when monitoring on other installations.

4. Monitoring optimization and expansion. This factor includes improving the accuracy of the average vibrations and refining the pump vibration limits identified in the initial setup. Once the database is complete, the number of monitored machines can be expanded.

4.1.1. Trend analysis applied to predictive maintenance

The trend analysis is a statistical method that enables the representation of the trendline of the process expected behavior. The most common application of this technique in research fields is to study the possible results of an operation, allowing the visualization of the most likely outcome [17].

When applied to the monitoring of centrifugal pumps, the trend analysis is implemented to prevent the machine from experiencing excessively demanding situations. This evaluation is a fundamental tool in preventive maintenance, since it provides a possible result before it happens, allowing for a margin to facilitate any repair that may be required.

When conducting a trend study, multiple factors besides the useful life of the machinery are managed:

- Cost reduction: By forecasting how the process can evolve, the automation of the system and the responses to problems is much more agile, reducing unexpected stops of the pump.

- Replacement parts optimization: By knowing the possible incipient errors, this method allows to prepare in advance the spare parts and the equipment necessary for the intervention.

- Decentralization: Having a constant monitoring of the equipment and a study of trends in progress, a repair team is not required in each pump installation, allowing personnel to be punctually sent as supervision.

- Productivity optimization: Using a trend inspection the control over the demand to which the pump is subjected to is much more accurate and it is possible to implement a more efficient production method.

By having such a wide range of advantages, trend analysis is one of the pillars of predictive maintenance and, thanks to digitalization, the knowledge of the centrifugal pump condition evolution is a constant over the monitoring process.

The uninterrupted monitoring of the centrifugal pump allows detecting the origins of the most recurring vibrations, applying to the prevention of damage and when they could appear.

4.2. Instrumentation

In order to apply a predictive maintenance method, very specific instrumentation is required, capable of measuring the main condition indicators of vibratory waves such as speed, acceleration and displacement of a specific element or component. The predominant equipment in the recognition of the state of a turbomachine consists of a series of sensors that allow the measurement of those parameters that adapt the scope of the analysis.

The instrumentation used in vibration analysis are very common sensors in the industry, since vibration is a simple harmonic movement that can be measured and displayed.. The difficulty when monitoring a pump does not reside in the data recording, but in its proper interpretation. The fundamental instrumentation while carrying out the analysis is [18]:

a) Piezoelectric Accelerometers [19]: The function of this instrument is to determine the acceleration of the vibration signal and it is the most widely used sensor in vibration analysis. It is a small and easy to install device, with a wide frequency range. They are permanently mounted on the machine casing, measuring the rotational vibrations of the pump and outputting a voltage proportional to the detected accelerations.

   Despite its usefulness, the accelerometer requires the integration of speed measurement tools in order to carry out its function. In addition to being sensitive to shocks and various power ranges, when connecting an accelerometer it is essential to know exactly the installation method and the model characteristics for the purpose of obtaining accurate measurements.

It is composed of a piezoelectric element, which implies potential differences and electrical charges on the surface of the material when subjected to mechanical stress. This element is compressed by a moving mass, exposed to the vibrations exerted on the sensor. When compressed, it delivers an electrical charge in the form of voltage, proportional to the stresses caused and, therefore, proportional to the local acceleration of the measured point. It has an amplifier and a connector to output the captured signal.

Figure 4.2.1. Piezoelectric accelerometer [20]

This transductor has been the only sensor installed during the project completion.

b) Proximity Sensors: These sensors have a very specific purpose, to prevent misalignment and deflection of the pads. They are used to measure the distance between the shaft and its support bearings to assess its vibration. By emitting an electromagnetic field, this sensor is able to change the field intensity when detecting the presence of an object.

c) Displacement Sensors: These are elongated devices with a coil at the end that simulates a magnetic field. As the conductor approaches the transducer and passes through the magnetic field of the sensor, Foucault currents are induced, reducing the field intensity and resulting in a lower continuous current.

They are hardy devices, but have a narrow frequency bandwidth between 0 and 1 kHz, being susceptible to electrical and mechanical shocks. They also require the installation of displacement sensors, dividing the movement of the bearing and the contact surface.

They come equipped with a conductor, an extension cable and a probe. A coil located at the tip of the probe generates an electromagnetic field and, in this field, a metal surface is positioned acting as the center of the induced currents. By placing this plate, the intensity of the field is altered. The variation corresponding to the electromagnetic field is measured and linearized by the conductor, which provides voltage proportional to the probe-target distance.

The measures registered by this sensor are in two directions, focused on two factors:

- Radial vibration measurement: Two probes are used, one directed to the X axis and a second one to the Y axis. The first component of the signal provides the average position of the shaft with respect to the bearings. The second component provides the peak-to-peak relative displacement of the shaft around its average position.
- Axial vibration measurement: The transductor provides the average axial position of the shaft and allows the monitoring of the load experienced by the bearing.
- Velocity measurement: A mark is made on the bearing and a determined voltage is generated each time the mark passes in front of the probe. That impulse is used in the speed calculation.
- Thermal expansion: The thermal differential and the expansion of the machinery is measured by comparing the X and Y axis distance measures.

d) Vibrometers: These are wave receptors that capture the electrical signal from the pump sensors and process the information from electrical impulses. This element filters and integrates, relying on the wave peaks, the electrical signal to determine the vibration levels.

e) Frequency analyzers: They are digital devices with integrated microprocessors, designed to recreate the FFT (Fast Fourier Transform), which allows the frequency spectrum of the wave to be represented as an acceleration function. They are similar to small computers, detecting defects due to imperfections associated with characteristic frequencies of the rotating elements resonance.

Once the instrumentation used when monitoring a centrifugal pump has been studied, choosing the transductor follows. It is unnecessary to install all the previously mentioned sensors since, in most cases, the only equipment demanded to determine the machinery condition are the accelerometers.

During the completion of this project the only transductors installed have been accelerometers and, consequently, the procedure is focused on the accelerometers selection in a lineal planification [21]:

1. Sensors characteristics: For the purpose of choosing the most suitable equipment for the installation, there are some transductors attributes that must be predefined.

    - Monitoring objectives: When installing accelerometers in a centrifugal pump, the provided data can be delivered as the overall RMS (Root Mean Square) or can describe all the information in the vibration signal. The RMS and the signal peaks are useful to control systems such as PLC or SCADA and, on the contrary, accelerometers employed in the recollection of a whole set of signal information are utilized to analyze the machine working frequencies. In some cases, both methods are applied.

- Sensor range: The bandwidth of a transductor refers to the range of frequencies it can accurately measure a signal without distortion. Bandwidth is a fundamental specification to consider when selecting a vibration sensor for a centrifugal pump vibration study.

- Environment condition: The humidity, the temperature and the impact propensity of the transductor are some of the characteristics that influence the equipment status.

- Precision of the sensor: The sensitivity and the calibration needs are also taken into consideration when selecting a transductor.

2. Safety Systems [22]: It is also necessary to select a transductor that is qualified by the manufacturer as "*SIL-Certified SIS/SIF*".

   A Safety Instrumented System (SIS) is a system designed to return a process to a safe status. A System Instrumented Function (SIF) is a specific function of the SIS. As an example, in the event of having a dangerous fluid flow rate passing through the pump, the SIS may be redirecting the fluid and a SIF of this SIS could be to stop the flow entrance into the machine.

   A transductor is qualified as SIL-Certified SIS/SIF when the Safety Integrity Level (SIL) and the SIS are constructed appropriately. The SIL varies from SIL 1 to SIL 4, having SIL 4 the lowest probability of SIS failure. Each installation requires a different SIL and SIS, so the detecting methods of each transductor must be studied in order to prevent equipment failures.

3. Installation directions: The accelerometers must be directed perpendicularly to the main vibrations generators, the bearings. Usually, a centrifugal pump consists of between two and four bearings: one set just before and after the motor, and the second set in front and behind the impeller. Ideally, measures should be performed in all three directions, vertical, horizontal and axial directions but it is frequent to install three accelerometers in the bearings between the motor and the impeller (vertical, horizontal and axially directed) and two transductors (vertical and horizontally directed) in the remaining bearings.

Figure 4.2.1. SG pump with accelerometers installed in the three directions

4. Installation techniques: Finally, when selecting a transductor it is a must knowing the mounting technique the pump demands. Depending on the surface, the space to install the sensors and the monitoring time, different techniques are followed, demanding the pertinent sensors:

   - Stud mounted technique: The sensor is mounted onto a stud attached to the machine casing. Is the most secure and reliable method, having the widest frequency response.
   - Adhesive mounted technique: The transductor is affixed to the surface with a special adhesive. This is usually applied when it is not possible to drill a hole for a stud.
   - Magnetically mounted technique: The sensor is connected to the machine by a magnetic base, and it is used when the accelerometer must be easily removable.
   - Probe tips or stingers mounted: The transductor is installed into the casing through a small opening. It is applied when the surface does not permit fixing a sensor on it.

Once the accelerometer model selected complies with both installation restrictions and requested features, the monitoring equipment can be safely and efficiently installed.

4.2.1. Piezoelectric accelerometers

Accelerometers are devices that have the capability of detecting the static and dynamic forces of the acceleration from a nearby element. They are able to measure and represent a vibration signal and, depending on its characteristics, the acceleration of an element can be measured in one direction (horizontal), two directions (vertical) or three directions (axial).

An accelerometer operating fundamentals can be compared to a mass compressing and decompressing a small spring. When it detects dynamic acceleration, the mass decompresses the spring until it moves with a proportional freedom to the acceleration it senses. The acceleration is then determined using this displacement value, working similarly to a proximity sensor.

Different types of accelerometers are used depending on their components. When intending to transform the mechanical motion of the mass produced by an element deviation into an electrical signal, typically three different kinds of accelerometers are used [19]:

- Piezoelectric accelerometers: These accelerometers are composed of a piezoelectric part that produces a voltage when it is under stress, which can be used to calculate the velocity and orientation of the force. This is the most focused sensor on the vibration analysis, and the accelerometer chosen for the completion of this project is a piezoelectric transductor.

- Capacitive accelerometers. Here, acceleration is sensed to generate capacitance, which is then converted into a voltage to measure the velocity values.

- Piezoresistive accelerometers: These specific accelerometers are made of a piezoresistive material and, when a force such as stress is applied to them, the piezoresistive part is deformed allowing to obtain the resistance change of that element.

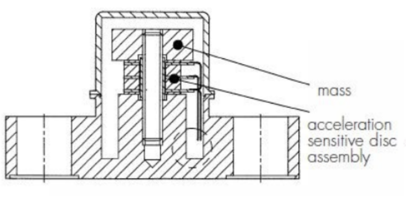


Figure 4.2.1.1. Piezoelectric accelerometer composition [23]

4.2.2. Differences between wireless and wired transductors

Due to the diversification of current measurement instruments, the difference between installing wireless and wired sensors is a point with great repercussions when determining the quality of the data collected [24]. Depending on the characteristics and capabilities of a sensor, different connections to the set to be monitored and specific measurement methods are required. Given the high specification of the transducer, it is selected based on the precision required for the correct machine monitoring.

It is possible to differentiate the qualities of each type of instrument from the following points:

- Cost: Wired sensors follow a complex installation process, increasing material, labor and settlement costs, since internal installation is often required.

- Autonomy: The most notable disadvantage of wireless sensors is that they are powered by batteries and, when the charge runs out, they must be replaced. Because of this, they must be in an accessible point to be able to replace them without inconvenience.

- Network security: Unlike wired sensors, wireless sensors require strong internal security to prevent data loss.

- Range: The main difference between wired and wireless sensors is the range that they can monitor without data loss. While wireless sensors have a limited range, wired ones vary by the installation extension and budget. A wireless transducer needs the gateway at a reduced distance, while a wired connection is more dependent on financial availability.

- Deviation avoidance ability: Wireless sensors need their own self-generated network to avoid interference between their position and the gateway.

- Power consumption: Wired devices constantly consume power, which can be very demanding for the electrical installation of the centrifugal pump.

- Functionality: A wireless sensor has very high precision and quality of the recorded data, above the usual wired transducers.

It is also important to note the process differences:

- Predictive inspections: For wired sensors, vibration measurements must be performed periodically (predictive route) for each installation (bimonthly or quarterly). Using wireless technology, all measured values are sent to a database for a further analysis, so it is not necessary to manually record the values.

- Alert comparison: Each time a predictive route is carried out, the measured values are compared with a preset alert level, generating a list of exceptions from the points that exceed the limits. By placing wireless transducers, alarms are received when the preset is exceeded or when unexpected changes occur, studying only the machines in alarm status.

- Diagnosis: When using wireless transducers, the diagnosis is made based on the machines that have caused the alerts, using only the data sent by the sensors that have detected a problem. In the case of wired sensors, the analyst in charge must study the list of exceptions so the graphs, spectrum and trends generation take longer.

In the case of having a pump, a machine or an installation that requires great precision and speed of action, it is preferable to prioritize wireless sensors in order to apply a predictive maintenance program, due to the ease they provide when making the diagnosis.

In the performance of this project, the instrumentation selected is completely wireless in order to achieve the main purposes of the implementation.

4.3. Monitored parameters

Vibration sources are often difficult to determine but, due to the distinctive propagation of these waves through the pump parts, the vibratory response fluctuates depending on which section of the machine is causing it. Knowing this, the data collection point must be located at the critical components of the machine, the bearings.

In order to monitor the equipment status, certain regulation parameters are required. The procedures to perform with the purpose of guaranteeing the integrity of the device are [29]:

1. Global vibration measurement:

Broadband global vibration measurements have the ability to set limits on vibration levels based on the wave frequency. The vibration levels of a centrifugal pump are collected in order to compare them with the machines under study when carrying out the vibration analysis. This method follows a three steps process applied for global vibration measurements:

a) Vibration level comparison to a fixed acceleration level: Firstly, a fixed level of the system acceleration is calculated to trace a line that follows the vibration peaks produced by the waves of a rotating machine in its functional state. The selected value is the highest point of the acceleration shown in the vibration plot and, in the event of detecting an acceleration exceeding the limit set, an alarm goes off.

b) Fast Fourier Transformation spectrum: The FFT, also known as Fast Fourier Transformation, is a method that aims to divide the complex vibration signal received through the vibration analyzer into its individual frequency components.

The FFT analysis is performed through the use of a specialized software that converts the data from the time domain to the frequency domain, which allows the signal to be decomposed into its frequency components. This method graphically represents the frequency patterns of the signal with the purpose of identifying the specific centrifugal pump problems. The FFT expression is based in the Discrete Fourier Transform (DFT) [30]:

$$X(k) = \frac{1}{N}\sum_{n=0}^{N-1} x(n) * e^{-j\pi kn/N} \qquad \textbf{(Eq. 4.3.1.)}$$

Where "$X(k)$" is the set of point in the frequency domain, "$x(n)$" are the time domain samples, "n" is the samples time index, "k" is the index of frequency data and "N" is the total number of input samples in the data collection. The exponential $e^{-j\pi kn/N}$ describes the sinusoidal waveform of the frequency domain.

By applying the FFT algorithm it is possible to reduce the iterations of the DFT in the order of 10^9. The DFT iterations for solving a system of N samples is of N^2 operations while applying the FFT the operations applied are $N * log_2(N)$. The FFT algorithm is more simple than the DFT, it follows the assumption of $n = 2r$ if "n" is even and $n = 2r + 1$ if "n" is odd:

$$X(k) = \frac{1}{N}\sum_{r=0}^{\frac{N}{2}-1} x(2r) * e^{-j\pi k2r/N} + X(k) = \frac{1}{N}\sum_{r=0}^{\frac{N}{2}-1} x(2r + 1) * e^{-j\pi k(2r+1)/N}$$

$$X(k) = \frac{1}{N}\sum_{r=0}^{\frac{N}{2}-1} x(2r) * e^{-j\pi k2r/N} + X(k) = \frac{e^{-j\pi k/N}}{N}\sum_{r=0}^{\frac{N}{2}-1} x(2r + 1) * e^{-j\pi k(2r)/N}$$

$$X(k) = \frac{1}{N}\sum_{r=0}^{\frac{N}{2}-1} x(2r) * e^{-j\pi k2r/N} + X(k) = \frac{e^{-j\pi k/N}}{N}\sum_{r=0}^{\frac{N}{2}-1} x(2r + 1) * e^{-j\pi k2r/N}$$

$$X(k) = \frac{1}{N} * x_{even}(k) + \frac{1}{N} * e^{-j\pi k2/N} * x_{odd}(k) \qquad \textbf{(Eq. 4.3.2.)}$$

c) Constant Bandwidth Method comparison: The CBM is a technique that compares the vibration amplitude of various frequency elements in percentages of the total spectrum.

   The CBM is carried out by using specialized software that determines if the vibrations of a component are increasing or decreasing with time because if the percentage of vibration is increasing over time, this could be indicative of a problem.

2. Measurement of specific vibration parameters for the detection of errors in the bearings:

Defects displayed on bearings can be very helpful when performing predictive maintenance on machines. These are transmission elements that are subjected to enormous forces that cause wear and, therefore, vibrations. Bearings are especially important in predictive maintenance because their imperfections can lead to high cost maintenance and working defects in the machine.

Bearings often fail due to wear caused by friction with contact surfaces. If the friction is excessive, they can damage the contact surface and create vibrations, generating unit malfunctions. In their best condition, they have little impact when rotating out of the load zone, producing a steady frequency in each harmonic. Because of this fact, bearing vibration frequency is a primary field.

3. Measurement of vibration parameters for the detection of defects in gears:

Gears are transmission components subjected to huge forces that do not rub against contact surfaces, but against the teeth of other gears. Due to the friction to which they are exposed, gears can suffer damage to their teeth, have too weak or too strong backlash when rotating, or receive wear on their teeth profiles. Although they are very durable, they are susceptible to wear over time. When a gear is functional, a noticeable acceleration peak appears at each harmonic as it rotates, also known as periodic soft shock effect. Unlike bearings, tooth wear does not cause damage to the machine, but creates higher internal stresses, meaning higher repair costs and longer repairs.

4. Waveform parameters, Symmetry and Amplitudes:

The symmetry or asymmetry and the crests height a wave presents are also crucial in vibration analysis. To understand the importance of graph symmetry, it is required to consider the crests and peaks that occur over time. The parameters responsible for this definition are Kurtosis and Skewness.

Kurtosis is a statistical variable that defines the distribution of the vibration amplitudes. It describes the shape distribution by flattering or sharpening the wave zeniths. In the event of detecting a high Kurtosis distribution, it is possible that there exist impacts, implying larger signal amplitudes.

Skewness is a statistical variable that shows the symmetry of the vibration amplitudes. It describes the symmetry distribution by deviating the wave to the left (negative distribution) or to the right (positive distribution). When the Skewness distribution is positive implies high amplitude vibrations while a negative distribution could indicate signal noise.

5. Vibration phase in harmonics and synchronous vibration measurements:

The vibration phase is the time lapse between the appearance of peaks from two waves of the same period and its importance resides in the vibration frequencies of the signals. In the event of detecting different frequency ranges, an unbalance or misalignment between two bearings can be diagnosed.

Studying the vibration phase also facilitates knowing the behavior of the machine rotative components. If the crests between the two waves are in synchronous phase the motor bearings and rotor are operating correctly, making sure that the engine is in good condition.

6. Subsynchronous vibration measurement:

It is well known that a motor is working in optimal condition when the harmonics of the waves produced by the elements under study are synchronized, but it is not uncommon that the harmonics are not synchronized and their crests do not coincide.

If one of the harmonic frequencies is equal to the fundamental frequency (the frequency of the main axis), the vibration will be subsynchronous. In this situation, the frequency peak of the component producing that coincident signal will occur immediately after the compared element harmonic.

Subsynchronous vibration implies that the element causing that late zenith operates at a lower frequency than the main axis. This may be due to bearing defects or turbulent flows in the impeller.

4.3.1. Bearings condition indicators

Bearings are machine elements that aim to increase the rotating efficiency by reducing the friction between the shaft and its support. By correctly positioning this piece, the supporting part is protected from the forces generated by the shaft when rotating. Furthermore, an additional function of these overdemanded elements is to prevent the misalignment of the shaft [25].

When focusing on predictive maintenance, these pieces are very accurately studied due to the incredible effort they do. In the event of finding a bearing defect, the reparation procedure may be hard to apply and can lead to expensive maintenance. Defects detected in bearings are the main causes of machine damage implying almost 60% of the faults, reason why it is important to take a deep view in their composition and working manners.

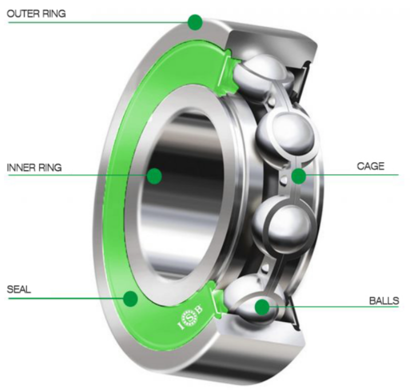


Figure 4.3.1.1. Bearing parts [26]

The rings are destined to the balls housing, permitting them to roll in between the rings surfaces. The rolling elements are equispaced by the cage, which allows the balls to rotate avoiding the collision with the rings surfaces. The cage aims to protect the balls from small loose debris. This specific composition makes the bearing a very efficient friction reducer.

The internal distribution of the rolling bearings is adapted to optimize the balls mobility inside the cage. The rolling elements produce less contact between themselves and the rings because they rotate as the rings move. This overimposed rotation implies that the dynamic friction between the shaft and the internal ring is reduced, never permitting it to suddenly stop:

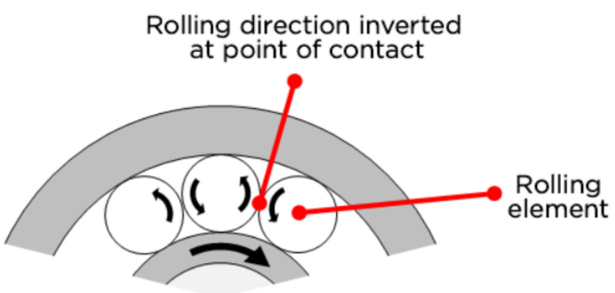


Figure 4.3.1.2. Internal mobility of the rolling balls [27]

As previously explained, bearings tend to fail due to some factors such as misalignment or unbalance but, in some cases, it is possible that these parts suffer from oxidation or internal damages. Due to their chemical composition, rust is not a common issue of these pieces but may afflict their stability.

On the other hand, surface damage, gear mesh or broken rotor bars are some defects that may be found when studying bearings condition [28]. For example, studying the velocity trend curve is very useful when unbalance and misalignment appear while the acceleration RMS and peak values curves are more focused on detecting gear faults, lubrication lack or rotor defects.

Here are represented some examples of the importance of studying the trend analysis for each parameter resides in the bearings:

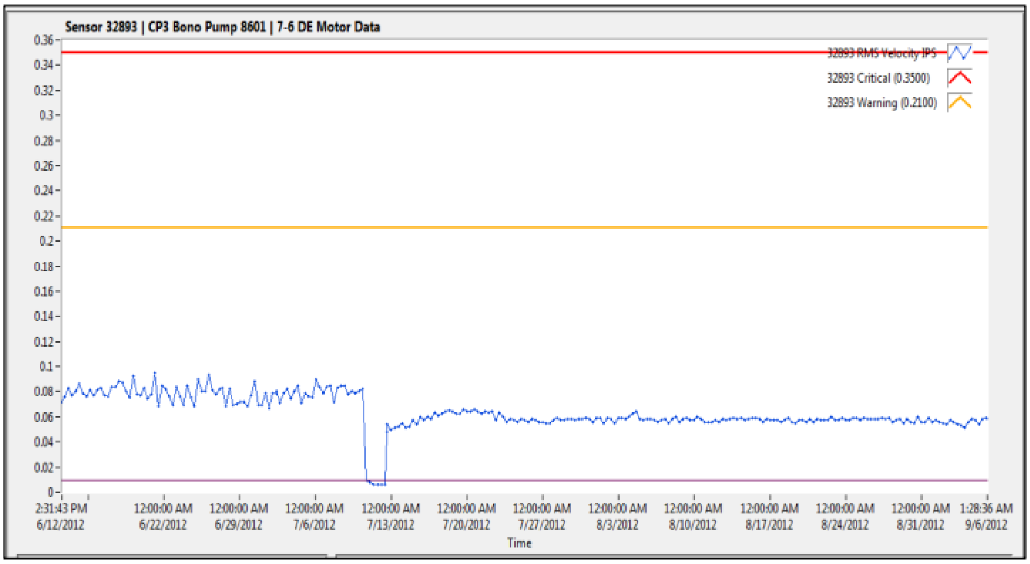


Figure 4.3.1.3. RMS velocity trend curve of a substituted faulted bearing [28]

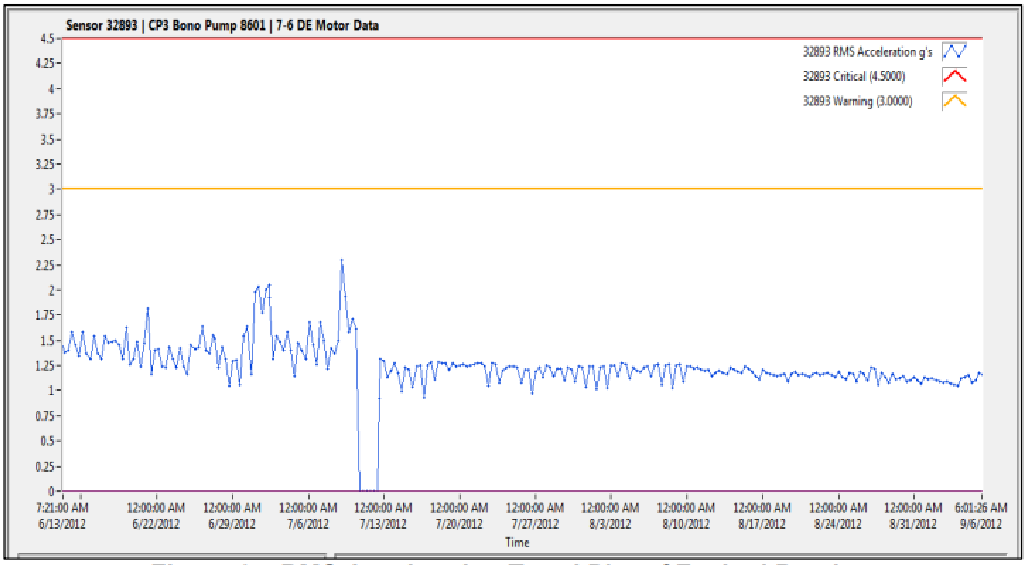


Figure 4.3.1.4. RMS acceleration trend curve of a substituted faulted bearing [28]

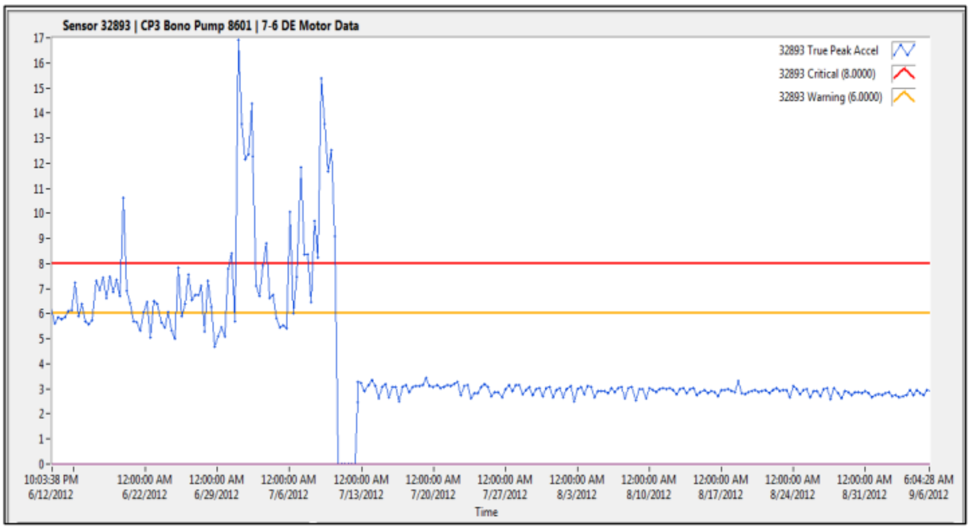


Figure 4.3.1.5. Peak acceleration trend curve of a substituted faulted bearing [28]

By completing some different trend analysis of multiple factors, the results may vary. As seen in Figures III.3. and III.4, the plots are unstable before the replacement but the alarms would have not gone off. Instead, Figure III.5. has shown the exceeded stop levels, demonstrating the multiple variables that afflict bearings faults. Applying various trend analysis is the only manner to prevent bearing or rolling elements damages.

To mainly comprehend the working conditions the bearings must be subjected to, some indicators can be calculated. For example, the basic rating life of the element and the dynamic loads it should be attached to in order to prevent premature failings:

1. Radial bearing dynamic load (K_r) in kiloNewtons:

$$G = \frac{G_{00} - G_r}{2} \qquad \textbf{(Eq. 4.3.1.1.)}$$

Where "G" is the maximum static axle box load in kiloNewtons, "G_{00}" is the maximum static axle load in kiloNewtons and "G_r" is the weight of the shaft divided by the momentum generated by all the bearings it is subjected to in kiloNewtons. These factors are defined by the mean radial load "K_r":

$$K_r = f_0 * f_{rd} * f_{tr} * G \qquad \textbf{(Eq. 4.3.1.2.)}$$

Where "f_0, f_{rd} and f_{tr}" are the payload, the dynamic radial and the dynamic traction factors, respectively. These are defined by the manufacturer and vary from 1 to 1.6.

2. Axial bearing dynamic load (K_a) in kiloNewtons where "f_{ad}" is the dynamic axial factor:

$$K_a = f_0 * f_{ad} * G \qquad \textbf{(Eq. 4.3.1.3.)}$$

3. Equivalent bearing load (P) in kiloNewtons where "Y" is the axial load bearing factor:

$$P = K_r + K_a * Y \qquad \textbf{(Eq. 4.3.1.4.)}$$

4. Basic rating life (L_{10S}) in million kilometers at a 90% reliability:

$$L_{10S} = \pi * ø * (\frac{C}{P})^d \qquad \textbf{(Eq. 4.3.1.5.)}$$

   Where "Ø" is the bearing diameter in millimeters, "C" is the basic load rating in kiloNewtons and "p" is the exponent for the life equation, that in bearings is rounded to 3.

Once the main equations are proposed, it is possible to know when the bearing will be prone to failure. These calculations are not the most frequent steps when determining the useful life of the element but may be a helpful tool when the machine is malfunctioning and it is required to approximate the loads the bearings should be subjected to.

4.4. Data collection

Through a constant follow-up of the components, the collection of non-significant data can be reduced and its quality improved for a later study in detail. According to the characteristics of the monitoring parameters, the data collection can be adjusted to the needs of the user and the centrifugal pump requirements. The instrumentation, the waveform, the intensity of the vibration and the internal elements are the parameters that most affect the data compilation, therefore, these factors are studied meticulously to get the most accurate data possible.

The characteristics of such parameters are divided into four main factors [29]:

1. The characteristics of the received signal, depending on:

   a) The transducers used in the monitoring: The instrumentation and its installation are mainly described by the most prone to produce vibrations elements of the machine, the bearings. In order to control the vibrations generated, multiple accelerometers are installed in each bearing. Depending on the machine, two or three accelerometers are connected to each bearing in the axial and radial directions.

Usually, a centrifugal pump is supported by two bearings, one at each side of the shaft, between the motor and the impeller. In the event of having a pump subjected to huge loads, the machine is supported by two more bearings, one at the motor and a second one at the casing, as commented in the instrumentation section. Therefore, the received signal varies in function of the own characteristics of the accelerometers, the number of transductors connected to the machine and their location and direction with respect to the bearings.

b) The magnitude studied: The three primordial magnitudes for a correct understanding of the condition of a turbomachine are the speed, acceleration and displacement of the system. Depending on the sensor used for the analysis the signal shows a different magnitude and, considering that the main sensor used in a centrifugal pump analysis is the accelerometer, the magnitude with a major importance is acceleration.

c) Wave amplitude: In order to properly describe the signal collected, the wave amplitude is studied. Depending on the peak to peak amplitude and the Root Mean Square (RMS), it is possible to approximate the wave intensity and the effective value of the signal, respectively. The RMS refers to the magnitude of a vibration in each direction. This method is very useful when studying a wave that varies over time, giving an averaged amplitude for a period of time.

2. Acquisition format: Vibration measurements are stored digitally in a database associated to a specific point of the diagram. The signal represented from the compilation can be traced in different domains and, depending on the domain, the graph response shows the acceleration as a function of frequency or represents the amplitudes over the time.

   The first acquisition from the accelerometers is a temporal plot, showing a plot of acceleration amplitudes over time. Once the FFT is applied, the acceleration amplitudes are described in a frequency domain.

   Knowing the status of the pump in a period of time can be useful to understand a machine condition but, for the purpose of detecting the vibrations origins, the frequency domain is much more appropriate. Detecting the acceleration peaks according to the internal frequency of the pump generates the plot studied when identifying a defect.

3. Vibrational order: This factor determines the severity of the vibration by quantifying its general energy, delimiting the vibration sources from a mean value.

   Intending to determine the severity of the wave, a filter is applied to the displacement, the velocity or the acceleration of the signal, in function of the parameter selected. The parameter chosen usually is based on the equipment ease to measure each of them. This filter implies a three spectrum study, each one with a different bandwidth:

   - Acceleration is studied from the 2 to the $2 * 10^4$ Hertz.
   - Velocity has a range of 10 to $1 * 10^4$ Hertz.
   - Displacement varies between 3 and 300 Hertz.

   In search of reducing the vibration sources, it is necessary to calculate the RMS of the magnitude under study inside the frequency filter applied to it. The RMS is estimated within the highest crests of the diagram and, depending on its results, the possible vibration origins are slightly reduced:

   - Low frequency range found in the displacement spectrum could imply: Unbalances, oil eddies/whip, binds and looseness.
   - Medium frequency range found in the velocity spectrum could imply: Unbalance, oil eddies, misalignment, binding, looseness and binding.
   - High frequency range found in the acceleration spectrum could imply: Bearings defects, misalignment, unbalance, cavitation, turbulence and friction. This is the most usual result if the machine is presenting an irregular behavior.

   Once the magnitude has been chosen and the RMS of the range has been calculated, the internal energy between two top points of the graph is studied, with the purpose of determining if the severity within the bandwidth is increasing. After repeating the process for multiple values and finding a frequency growth in the spectrum, it can be guaranteed that the internal energy is growing too. This fact implies the bearing malfunction or the appearance of phenomena such as cavitation and turbulence.

Once the characteristics of the parameters that most affect the data compilation are defined, it is possible to perform a correct measurement interpretation and determine the sources of vibration.

4.4.1. Alarm and stop levels regulations

The first step when determining if there exists a possible defect afflicting the centrifugal pump is observing the trend analysis behavior. This system allows predicting the result of a process by determining statistically probable defects. Once the trend line exceeds a preset alarm level, the cause of exceeding the limits is investigated.

The alarm limit is usually divided into two: an excessive point that exceeds the safety grade of the equipment and an unexpected significant change. These alarms are defined according to the manufacturer recommendations and the ISO-API standards [ANNEX I], the security regulations. The risk the collected data exposes is determined by the range of the previous alert threshold [31]. If the regulations and the manufacturer are demanding very low acceleration peaks, the alarm range is set to a lower acceleration. In the event that the pump has broader safety standards, the machine will be subjected to study when the unexpected changes alarm level is exceeded. The machine is not stopped until the second range is exceeded, except in unusual cases that need safety examinations.

Commonly, when defining these alarm and stop frequency levels, the centrifugal pump distributors study the behavior of operating machines and establish the safe frequency bandwidth. In order to calculate those regulations, there are three main analysis to carry out:

1. Frequency domain spectrum: The most important analysis is the frequency spectrum, that allows searching for periodic shapes and predominant frequencies to find abnormalities. As previously commented, to acquire a graphical representation of the vibration waves in the frequency domain, the FFT algorithm is applied.

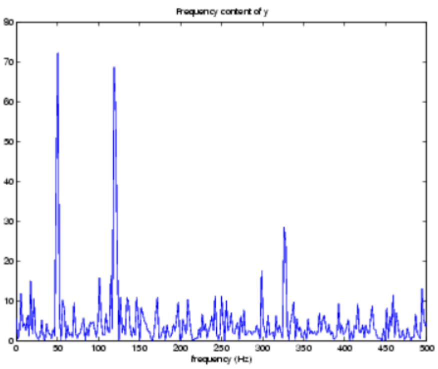


Figure 4.4.1.1. FFT Recreation for the frequency domain [30]

2. Waveform analysis: When unusual wave behaviors are found, it is necessary to determine if there exists an unexpected distribution of the wave shape. In this analysis, it is frequent to apply Skewness and Kurtosis to determine the specific distribution in a time domain. It is a simple comparison that, if it may be damaging for the machine, is studied in depth. Some primordial goals of this study are to find periodic behaviors of the waveform, unusual distributions and synchronous oscillations.

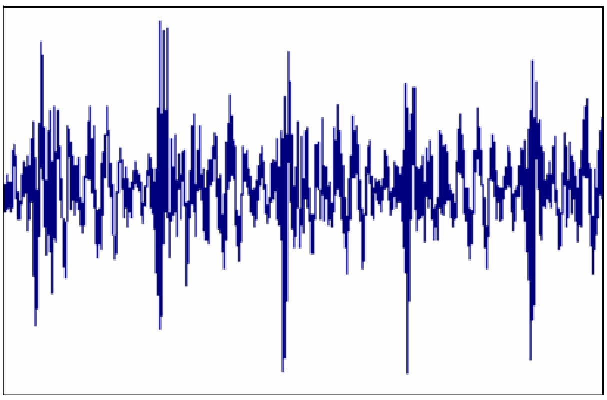


Figure 4.4.1.2. Self made usual vibration wave in time domain

3. Envelope analysis: In the event of not detecting failure indicators in the waveform analysis nor the frequency spectrum, it is important to redirect the study to a different bandwidth. After applying the FFT and studying the frequency spectrum, an envelope analysis is applied. The envelope analysis finds its basis on the zoom of the frequency spectrum, adjusting the frequencies in a low or high bandwidth to study what is happening in a specific lapse.

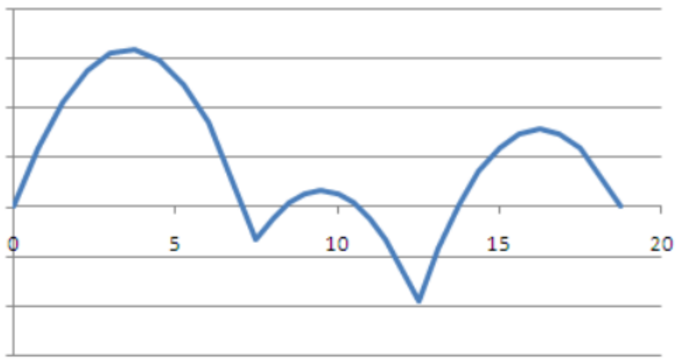


Figure 4.4.1.3. Envelope curve simulation [32]

Three procedures are usually carried out in this analysis:

- Wave rectification: The time spectrum is manipulated to compare the negative acceleration points with the positive peaks.

$$y(t) = |x(t)| \quad \textbf{(Eq. 4.4.1.1.)}$$

Where "$y(t)$" is the resulting wave once inverted the negative peaks in a time domain and "$x(t)$" is the original time spectrum.

- Pass filter: After rectifying the curve, the high or low frequency ranges are deleted from the plot in order to reduce the study area.

$$z_1(t) = \sum_{n=0}^{N-1} \frac{y(t-n)}{N} \quad \textbf{(Eq. 4.4.1.2.)}$$

$$z_2(t) = \sum_{n=0}^{N-1} \frac{y(n-t)}{N} \quad \textbf{(Eq. 4.4.1.3.)}$$

Where "N" is the number of significant points of the rectified curve, "$z_1(t)$" is the low frequency range filtered signal and "$z_2(t)$" is the high range filtered signal.

- Demodulation of the envelope: The last stage is to take the highest frequency point at each time interval.

$$h(t) = max(z(t)) \quad \textbf{(Eq. 4.4.1.4.)}$$

Where "$h(t)$" is the enveloped signal depending on time, that only considers the maximum values of each peak set at a high or low range.

Once the distributors have considered all these three analyses, the alarm levels can be established by considering the significant parameters status. Some of these parameters are the temperature, pressure, velocity and acceleration. In the event of detecting unexpectedly high frequencies that may produce damages to the equipment, the alarm is activated in order to solve the possible defect. If the defect has appeared and has produced the stop alarm to be activated, the machine must be shut down for safety reasons.

The threshold of these alarm levels depends on the Root Mean Square (RMS), which consists of obtaining measures over time:

$$RMS = \sqrt{\frac{1}{N}\sum_{n=1}^{N} x_n^2} \qquad \textbf{(Eq. 4.4.1.5.)}$$

Where "N" is the number of points in the period and "x_n" is each frequency value in Hertz.

In the alarm level, the RMS is set based on the whole filtered curve, and in the stop level, the RMS is set depending on the enveloped result, resulting in a higher frequency level.

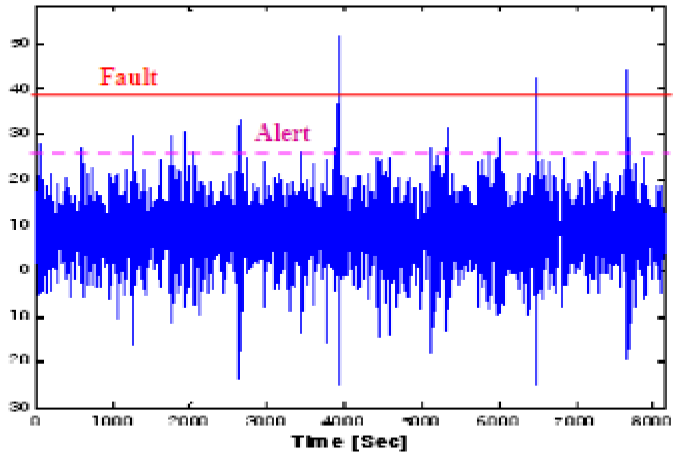


Figure 4.4.1.4. Acceleration - Time spectrum, alert and fault levels [31]

The alarm and stop levels selection for the *G3 SG II* can be found in the [ANNEX IV].

5. WIRELESS EQUIPMENT PROCEDURE

The equipment selection and configuration is the initial step to complete this report objectives, constituting the first and most important practical component of the project. In order to highlight the importance of the equipment specifications, it is primordial to remember the document goals. This report is focused on the elaboration of a practical guide for selecting, configuring and installing a fully wireless vibration acquisition system in order to, by updating the current monitoring procedures, apply a predictive maintenance model in an Aigües de Barcelona centrifugal pump.

Aiming to achieve these goals, it is required to know which equipment is under study. The pump selected is from the *SG* set, Group 3 and Installation II and, at this point, it is necessary to select the proper monitoring equipment and configure it.

Some commented points are recalled in order to understand how the data is analyzed:

- Centrifugal pumps: It has been highlighted what is the object analyzed, how it works and the impact it has in every field it is destined to.
- Vibrations: What these waves are and how they can damage the machinery.
- Instrumentation: The elements implemented in the centrifugal pump subjected to study, the critical components analyzed and how to select and install the monitoring systems.
- Regulating parameters: The importance of the displayed results and the methods used when studying those outcomes.
- Monitoring parameters: The value of each decision taken when looking for a specific goal, how each parameter from both the elements used and their configurations are determinant when implementing a predictive maintenance method.
- Regulations and standards: A reminder that the instrumentation, the pump and the analysis procedure must follow a set of safety principles.

At this point, it is possible to understand the vibration analysis procedure and to begin with the data interpretation. However, it is required to take a deep view in the equipment installed to comprehend how the data collected is obtained.

Wireless equipment data collection is based on a set of sensors sending signals to a gateway:

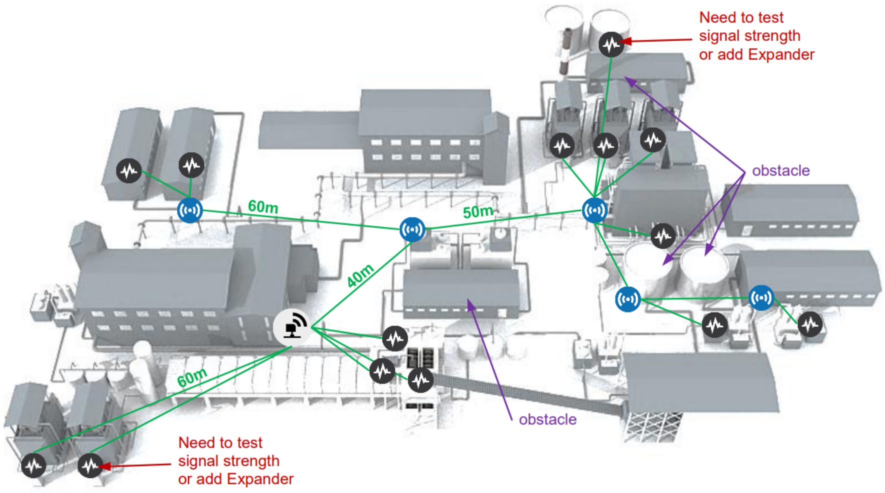


Figure 5.1. Wireless sensors data procedure in a station [33]

After receiving the signals, the gateway resends the signal to the cloud, in order to clean and analyze the results of the collected transmission:

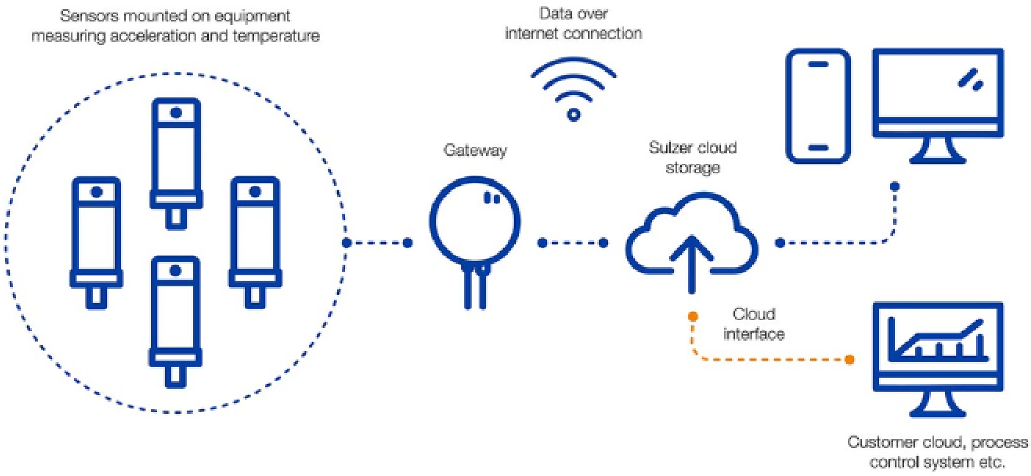


Figure 5.2. Full wireless data collection procedure [34]

5.1. Centrifugal pump under study

As previously commented, the equipment must be configured in function of the pump characteristics. The centrifugal pump used for this study pertains to the *G3 SG II* stage of Aigües de Barcelona. The pump under study is supplied by "*Xylem*", the pioneer supplier of water technologies, focused on solving all necessities related to water issues. The centrifugal pumps operating at *G3 SG II* are: Lowara e-NSC - Suction pumps in cast iron.

Lowara e-NSC suction pumps are designed and prepared for the water transport, fire protection systems and very many industrial utilities. The e-NSC equipment is focused on high efficient performances, in order to control the variative fluid flux of huge installations. This implies lower energetic consumption and costs.

Lowara also prepares robust machinery to prevent internal and external damages of the pump, including replaceable and resistant wear rings and a four bearing set for greater stability. Due to its installation flexibility, the maintenance and repairing procedures are facilitated, reducing inactivity.

Because of these characteristics, configuring the acquisition system for the Lowara e-NSC centrifugal pump is a simple and one directed process. The technical specifications of the pump can be found in the [ANNEX III].

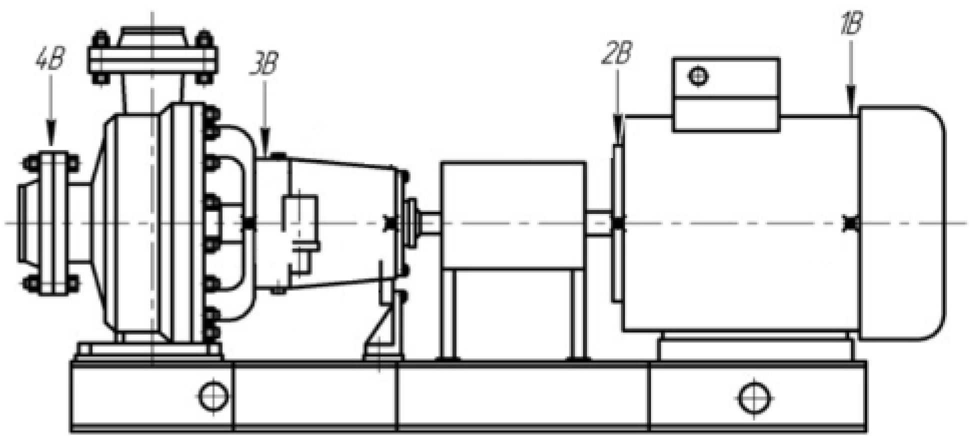


Figure 5.1.1. Bearing locations for Lowara e-NSC [1]

5.2. Instrumentation selection

As previously commented, when selecting the best accelerometer it is primordial to take into account the factors that define the characteristics of the transductor. Recalling these factors:

- Sensor characteristics.
- Safety systems.
- Installation directions.
- Installation techniques.

In order to complete the implementation procedure successfully, some piezoelectrics accelerometers and their acquisition systems must be compared. The four accelerometers that have the demanded qualities to properly monitor an Aigües de Barcelona - *SG* centrifugal pump are:

1. Fluke 3563: An analysis vibration sensor system implemented by Fluke.
2. SKF Enlight Collect IMx-1: A mesh sensor network for data collection.
3. Acoem EAGLE: A monitoring system focused on critical rotating machinery.
4. PCB Echo Wireless Vibration Monitoring System: An eight channel industrial junction box converter of sensors to wireless operation.

With the purpose of selecting one type of transductor, the main characteristics of each system are presented. All the specifications commented by the manufacturers are exposed in the next pages but not all the characteristics are necessary in the implementation of this project objectives. Because of this, it will be discussed which accelerometer is selected with the mainly required specifications after presenting the products complete features.

The following specifications have been taken from the manufacturers overviews and websites, so each product has the references and links the manufacturers provide, see full specifications in [ANNEX III].

1. Fluke 3563 [35]:

Vibration sensor system:

- Transmission interval: Configurable to a minimum of 10 minutes
- Frequency range: 2 Hz - 10 kHz in the Z axis and 0 Hz - 1 kHz in the X and Y axes
- Amplitude range: ± 50 g in the Z axis and ± 16 g in the X and Y axes
- Sampling frequency: 18.5 kHz - 62.5 kHz
- Temperature measurement and storage range: -20°C - 85°C
- Size: 68mm x 53.4mm
- Weight: 199.5g
- Ingress protection class: IP67
- Shock Limit: 5000 g peak
- Power: 6 x 3.6V 1/2 AA Li-SOCl batteries
- Battery lifetime: 1 - 2 years
- AD Conversion: 24 bit

Wireless communication (sensor to gateway):

- Radio Frequency: 2.4 GHz ISM band according to IEEE 802.15.1
- Range: Up to 100 meters, depending on environment

Gateway:

- AC main power: AC input 85-264 VAC, 0.35A/115V, 0.25A / 230V, 47-63 Hz
- Power-Over-Ethernet: Compliant with IEEE 802.3af
- WIFI: IEEE 802.11 ac/a/b/g/n
- WIFI Security: WPA/WPA2
- Ethernet: 10/100/1000 MBits/s
- Ingress protection class: IP67
- Temperature operation: -20°C to 60°C
- Temperature storage: -40°C to 80°C

Figure 5.2.1. Fluke accelerometer and acquisition system [35]

2. SKF Enlight Collect IMx-1 [36]:

Vibration sensor system:

- Frequency range: 10 Hz - 10 kHz in the Z axis and 0 Hz - 1 kHz in the X and Y axes
- Amplitude range: ± 50 g in the Z axis
- Sampling frequency: 50 Hz - 10 kHz
- Temperature measurement and storage range: -40°C - 85°C
- Size: 80mm x 33.7mm
- Weight: 142g
- Ingress protection class: IP69K
- Power: Industrial range 24 V DC or Power over Ethernet (PoE)
- Battery lifetime: 4 - 8 years
- AD Conversion: 128 bit

Wireless communication (sensor to gateway):

- Radio Frequency: Mira mesh low energy mesh radio network (2.4 GHz ISM band)
- Range: 10 - 30 meters

Gateway:

- AC main power: Industrial range 24 V DC or Power over Ethernet (PoE) / V DC input: 24 V DC (9-36 V DC); 7.5 W / PoE input: 48 V DC (44-57 V DC); 7.5 W
- WIFI: 802.11 a/b/g/n/ac, 2.4 and 5 GHz
- WIFI Security: WPA2-Personal and WPA2-Enterprise
- Ethernet: 10/100/1000 MBits/s
- Ingress protection class: IP65
- Temperature operation: -20°C to 60°C
- Temperature storage: -40°C to 60°C

Figure 5.2.2. SKF accelerometer and acquisition system [36]

3. Acoem EAGLE [20]:

Vibration sensor system:

- Transmission interval: Smart interval
- Frequency range: 1 Hz to 15 kHz for Z axis - 6 kHz for X and Y axes
- Amplitude range: ± 50 g peak, 24 bits
- Sampling frequency: 256 Hz - 51.2 kHz / FFT max 100 Hz - 20 kHz
- Temperature measurement and storage range: -20°C - 70°C
- Size: 48 mm x 113mm
- Weight: 403g
- Ingress protection class: IP67
- Vibration and Shock Limit: 500 g peak / 5000 g peak
- Power: 48 V, 0.3 A, PoE injector (IEEE802.3.af)
- Battery lifetime: 5 years
- AD Conversion: 24 bit

Wireless communication (sensor to gateway):

- Radio Frequency: 2.4 GHz ISM band International license-free
- Range: Up to 100 meters

Gateway (EAGLE EDGE):

- AC main power: 48 V, 0.3 A, PoE injector (IEEE802.3.af)
- IT and networks: TCP/IP, HTTPS, HTTP, DHCP
- Ethernet: 10/100 Base-T Ethernet Channel, RJ45 connector
- Ingress protection class:IP67 and IP68
- Temperature operation and storage: -20°C to 60ºC

Figure 5.2.3. Acoem accelerometer and acquisition system [20]

4. PCB Echo Wireless Vibration Monitoring System [33]:

System overview:

- Frequency range: 4 - 2300 Hz
- Sampling frequency: 61.4 kHz
- Temperature measurement and storage range: -20°C - 85°C
- Size: 203 x 102 x 152mm
- Weight: 1290 g
- Ingress protection class: IP66
- Power: 24 VDC 2.2 mA 0.75 mW
- AD Conversion: 16 bit

Figure 5.2.4. PCB accelerometer and acquisition system [33]

Once the specifications of each vibration sensor system have been presented, the demanded characteristics for the proper analysis of a centrifugal pump are compared:

a) Frequency ranges: The frequency ranges are the capacity of measuring wave frequencies that, in this project, are at most 7 kHz The PCB component has an insufficient bandwidth, so this system is discarded. The other three components have a wide range of frequencies, highlighting Acoem EAGLE, so all the systems could be implemented in a centrifugal pump.

   1. Fluke 3563: 2 Hz - 10 kHz
   2. SKF Enlight Collect IMx-1: 10 Hz - 10 kHz
   3. Acoem EAGLE: 1 Hz to 15 kHz
   4. PCB Echo Wireless Vibration Monitoring System: 4 - 2300 Hz

b) Amplitude ranges: The amplitude ranges are referred to the capability of the systems to measure wave amplitudes that, in this case, are at most 10g. The amplitude range of the three remaining components is appropriate for the purposes of this project.

1. Fluke 3563: ± 50 g
2. SKF Enlight Collect IMx-1: ± 50 g
3. Acoem EAGLE: ± 50 g
4. PCB Echo Wireless Vibration Monitoring System: Without specification

c) Maximum shock levels: It is the capacity of the system of withstanding impacts with no damage. Centrifugal pumps are normally prepared to endure almost 10 g. The SKF has not shown a clear specification for this parameter, so if this component is selected at the end of the comparison, it should be asked to the distributor.

1. Fluke 3563: 5000 g peak
2. SKF Enlight Collect IMx-1: Without specification
3. Acoem EAGLE: 500 / 5000 g peak
4. PCB Echo Wireless Vibration Monitoring System: Without specification

d) Temperature ranges: The working environment at Aigües de Barcelona is humid, so the sensor should be adapted to a high humidity and temperature range. All the three products have a very similar temperature range, but the Fluke component does not show a humidity resistance, so in the event of selecting this product, it would be necessary to ask the distributor about its humidity resistance.

1. Fluke 3563: -20°C - 85°C
2. SKF Enlight Collect IMx-1: -40°C - 85°C (95% humidity limits)
3. Acoem EAGLE: -20°C - 70°C (95% humidity limits)
4. PCB Echo Wireless Vibration Monitoring System: -20°C - 85°C

e) Sampling frequency: It is the amount of measures in a brief period of time. In a centrifugal pump analysis it is usual to consider a bandwidth of 500 Hz to 7 kHz. The Fluke 3563 has an incredibly high sample frequency, but does not consider low bandwidths, so the SKF and the Acoem components have a major disponibility for a centrifugal pump analysis.

1. Fluke 3563: 18.5 kHz - 62.5 kHz
2. SKF Enlight Collect IMx-1: 50 Hz - 10 kHz
3. Acoem EAGLE: 256 Hz - 51.2 kHz / FFT max 100 Hz - 20 kHz
4. PCB Echo Wireless Vibration Monitoring System: 61.4 kHz

Once compared all the four vibration systems, the Acoem EAGLE is selected. This product perfectly fits for the implementation of a predictive maintenance system of an Aigües de Barcelona centrifugal pump, standing out over the other possibilities. Furthermore, the range of its wireless communication is between 70 and 100 meters, giving a great margin to install the acquisition system at a certain distance from the transductors.

Acoem EAGLE is selected due to Acoem being a very reliable supplier of transductor and, multiple times, Aigües de Barcelona has trusted Acoem for the implementation of their projects. It is also important to emphasize that in [ANNEX III] the specifications of the pumps installed at *SG* are described and, the EAGLE acquisition system, perfectly fits the requirements of the machines.

The data collection of the Acoem EAGLE follows a specific procedure, very similar to any different accelerometer only varying in how some steps are carried out [20]:

1. Adapting the surface to install the accelerometer: First of all, the centrifugal pump must be cleaned, withdrawing any residue remaining in the surface.

2. Installation of the accelerometer: Acoem recommends for the EAGLE system an adhesive mounted technique, using a double sided adhesive tape Acoem provides with its products. However, it has been decided to mount it using a triaxial mounting technique.

3. Data acquisition configuration: The accelerometers and the acquisition system are connected by the EAGLE Manager, the software Acoem facilitates for the monitoring of turbomachinery. In order to configure both items, Acoem provides some instructions:

   - Download the EAGLE Manager software on a computer and connect it to the acquisition system (the gateway) via USB. A gateway is a connection device that allows the communication between different systems, such as the cloud and the transductors. It is used as a database before sending all the results to the cloud.
   - Turn on the accelerometers and revise if the gateway, the EAGLE EDGE in the case of this study, is close enough to the transductors to get the data with no deviations.
   - Open the software and add the accelerometers, specifying the type of transductor it is. In this project, it is a piezoelectric accelerometer.
   - Adjust the regulating and monitoring parameters and connect the system to the wireless connection used for the analysis (Wi-Fi, Bluetooth…).
   - Establish the connection between the gateway and the accelerometer.

4. Status verification: Assure that the accelerometer is properly installed and connected.

When this process is completed, the acquisition system is ready to collect and process data.

5.2.1. Equipment installation

The installation procedure requires to consider a wide range of factors that may afflict the reliability of the data collected and the lifetime of the equipment. Acoem EAGLE is a fully wireless vibration acquisition system, so the wire installation issues are totally avoided but implies an accurate configuration protocol in order to receive the most precise information possible [33]:

1. Field planning: The first step is to measure the distance between the machines that require monitoring and the possible location for installing the gateway. This project is centered on installing accelerometers in one pump, so the distance measures are not required but keeping in mind the limits of wireless communication.

2. Characteristics of the accelerometers: Acoem EAGLE specifications have been detailed in the previous section. The expected lifetime, the collecting capacities and the distributor recommendations are fundamental to properly install an accelerometer on the machine. As mentioned, the expected lifetime of the EAGLE is five years and, in order to monitor the centrifugal pump for fifteen years, three sets of accelerometers are needed. EAGLE transductors are triaxial, meaning that can collect data from the three axes by being installed in a radial axis. Triaxial transductors are normally installed on the vertical axes of the bearings but, in this case, Acoem recommends installing their sensors on horizontal axes.

3. Amount of accelerometers installed: Vibration transductors must be installed at the bearings of the pump and motor. Usually, centrifugal pumps are composed of two bearings, one at the impeller and a second one at the rotor. Lowara e-NSC, the pump at the *SG* sets, is a bed-mounted centrifugal pump composed of four bearings, demanding four sets of transductors, one for each bearing.

   As Acoem EAGLE is a triaxial sensor, it is only necessary to install one at each bearing, collecting the data along the three axes. As the expected lifetime for an EAGLE transductor is five years and the project duration is fifteen years, the total amount of transductors required to monitor the vibration of a centrifugal pump at *G3 SG II* is twelve accelerometers.

4. Mounting technique: The transductor could be affixed to the surface with a special adhesive recommended by the supplier. This is usually applied when it is not possible to drill a hole for a stud but, in this case, Lowara e-NSC could be drilled.

   The adhesive option has been discarded due to the duration of the project. In fifteen years, the adhesive should be replaced for new ones that could be differently dimensioned, implying a new cleaning procedure when mounting the new transductors. For this reason, it has been considered the triaxial mounting technique more suitable for this report.

5. Installation locations: Accelerometers must be directed perpendicularly to the main vibrations generators, the bearings. Usually, accelerometer sets are installed just before and after the motor, and in front and behind the impeller. Ideally, measures should be performed in all three directions, vertical, horizontal and axial directions but it is frequent to install three accelerometers in the bearings between the motor and the impeller (vertical, horizontal and axial) and two transductors (vertical and horizontally directed) in the remaining bearings.

   In this project completion, the transductor selected has been chosen taking into account the installation procedure. Acoem EAGLE is a triaxial transductor meaning that it is possible to only install one of them at each bearing. The locations defined are the horizontal axes of both bearing sets, the rotor and the impeller.

6. Installation procedure: To mount the accelerometers a flat surface is ensured. A M8 2mm hole is drilled with a centered Ø6.8 mm hole. Then, the stud and the washer are screwed to the transductor and assembled to the machine. It is necessary to consider the directions the accelerometer has marked on it to install it in the proper directions. Once connected to the machine, the sensor is turned to be aligned to its axes.

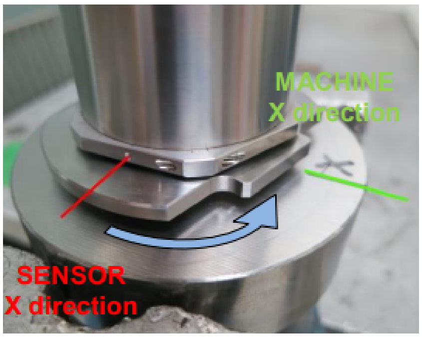


Figure 5.2.1.1. Rotation of the transductor to align the axes [33]

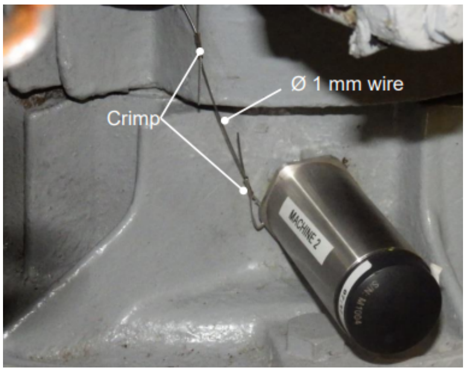


Figure 5.2.1.2. Acoem Eagle accelerometer installed [20]

7. Ensuring the collection reliability: Once the four accelerometers have been installed they must be calibrated. In order to calibrate the accelerometers, a calibrator is needed. Calibrators are portable devices prepared to adapt the measures of some transductors avoiding the environment impedances. The calibrator is connected to the EAGLE devices one by one. Once it has been activated, it starts showing the calibration results. When the acceleration outputs correspond to the calibrator results, it is ready to collect.

8. Environmental considerations: Aigües de Barcelona is a leading company in the sector of water management. Their stations are formed by tens of centrifugal pumps that propel and transport water. The humidity generated by the unstoppable water cycle is an important factor that may afflict the accuracy of the data collection. In order to avoid it, the EAGLE EDGE is prepared with a humidity function that, by introducing the mean humidity of the installation point, avoids the water interference. The relative humidity of an Aigües de Barcelona station is around 55%, supposing no inconvenience for the EAGLE system.

   Moreover, the temperature of the terminal is also a main factor to consider. The stations of water transport are normally prepared for keeping a 25°C temperature but the unstoppable rotation of the machinery can produce an increase of temperature at the bearings, achieving 60°C. Acoem EAGLE is prepared for withstanding almost 70°C, being able to endure the heat increment even in the worst circumstances.

9. Gateway installation: The gateway is mounted on a wall, between 3 and 100 meters from the EAGLE accelerometers. It must be installed 1 or 2 meters above the centrifugal pumps so, in this case that the pumps are bed mounted, it should be installed 4 meters from the ground. It is connected to an arm facilitated by Acoem that is drilled to the wall. Once it has been installed, it is necessary to connect it to a power and ethernet provider by a unique wire. This must be taken into consideration when deciding the field planning.

Figure 5.2.1.3. Acoem Eagle gateway arm [33]

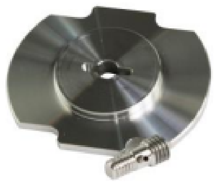


Figure 5.2.1.4. Acoem Eagle washer and stud [33]

10. Gateway connection to the EAGLE web interface: It is important before connecting the gateway to the accelerometers to configure it. It is linked to a device with access to the internet to open the EAGLE interface. This interface can be accessed by introducing the code Acoem provides with their EDGES.

11. Gateway - Accelerometers connection: The connection between the EAGLE and the EDGE has been previously explained. This configuration is a very delicate procedure that determines the results reliability. It is a main factor when applying a predictive maintenance model that requires an incredibly wide knowledge about the machinery and equipment under study.

12. Accelerometer power - up: To activate or reset the sensors it is necessary to take a magnet Acoem supplies with their products. It is a 4 kg magnet that, by approaching it to the transductors caps, activates the piezoelectric element of their inside.

13. Second ensurance: After having installed and connected the accelerometers and the gateway, it is necessary to verify the data collection. In the event of having properly settled the conditions of the equipment and the characteristics of all the factors, the resulting collected data will be clean and precise, implying the future efficiency of the installation.

5.2.2. Data acquisition process of the selection

The first step before executing a vibration analysis is to prepare the data collecting equipment [21]:

1. Installing the accelerometer: As commented before, the Acoem EAGLE transductor is fixed to the pump by the triaxial mount. To mount it, a stud and a washer are screwed to the transductor and assembled to the machine. It is necessary to align the directions the accelerometer has marked on it and the machine axes, to install it in the proper directions.

2. Connection to the acquisition system: The accelerometers are connected via Wi-Fi with the gateway, the EAGLE EDGE, where the system stores all the data obtained in a temporary database. After the measurement is completed, the data is sent to the cloud and the storage of the EDGE is deleted to free up space.

3. Data transmission: The stored data is sent to the cloud following the *Message Queuing Telemetry Transport* (MQTT) protocol. The MQTT protocol is designed for data transmission between sensors and devices of IoT (Internet of Things), a collective network of communication between devices and the cloud. EAGLE EDGE publishes the data in the cloud for a posterior interpretation. This protocol works through a restricted bandwidth and reduced frequency networks, guaranteeing the security of the information.

4. Data processing: The Acoem EAGLE software [38], the EAGLE Manager, is programmed in order to process and analyze the data collected. The software is prepared with the wished systems parameters, such as:

   a) Sensor selected: In this project, the sensors are piezoelectrics accelerometers.

   b) Sampling frequency: Usually, when monitoring the vibrations generated by a centrifugal pump, the sampling frequency demanded is in between 500 Hz - 7 kHz (taking into account the highest and lowest crests) and the Acoem EAGLE has a range of 100 Hz - 20 kHz sampling frequency.

   c) Filters: Filters are used to delete wave noise. These are not necessarily applied, at least it is appreciated an incipient defect on the bearings. There exist three kinds of filters: high frequency filter, low frequency filter and specified frequency filter. In the event of detecting a peak outside the bandwidth, it is deleted from the spectrum.

   d) Monitoring cycles: The monitoring cycles are the intervals that the sampling frequency requires to complete a full data iteration. It needs between 20 minutes and 1 hour, depending on the firsts responses of the system.

   Once the processing is completed, data analysis is automatically applied.

5. Result interpretation: After having obtained the results of the analysis, these are presented on an interface following the MQTT protocol. The analyst in charge studies the results shown at the interface and takes the decision of applying or not maintenance to the defect detected.

6. Solution implementation: If it is decided that the problem requires an intervention, the repair team springs into action.

7. Unstopped monitoring: The cycle is repeated in order to keep the machine in good condition for as long as possible and extend its lifetime.

5.3. Gateway configuration

In order to configure the EAGLE EDGE, it is necessary to access the gateway interface using a device with access to the internet. Once introduced the link Acoem provides with their gateways, the interface configuration appears. To access, the password and user are required. The user given by the supplier is divided into manager and user. The manager credential is centered on configuring the characteristics of the acquisition system while the user is more focused on the data interpretation.

The configuration commented below has not been applied yet. As it has been explained, the purpose is to apply the wireless monitoring in a centrifugal pump at *G3 SG II*, so the configuration shown in the following section is the one that, when this project is completed, will be implemented. The interface figures have been taken from the [33].

Once the manager password has been introduced, the system settings are displayed:

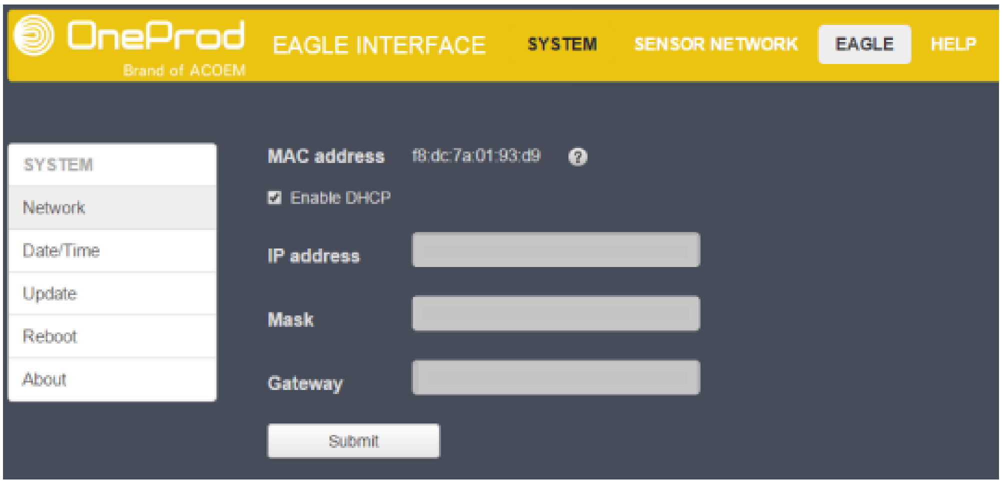


Figure 5.3.1. OneProd interface system tab [33]

The IP address, the mask and the gateway are automatically fulfilled by the computer used for the configuration. As seen in the left tree, there are a few options to modify before configuring the gateway, such as the date, the timezone and the uploader. The update tab is the last part of the configuration, once all the modifications have been prepared the system must be updated.

By having introduced the basic information, the sensor network settings modifier is activated:

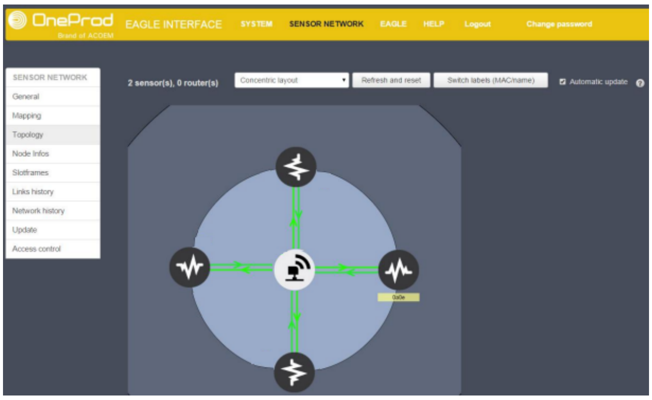
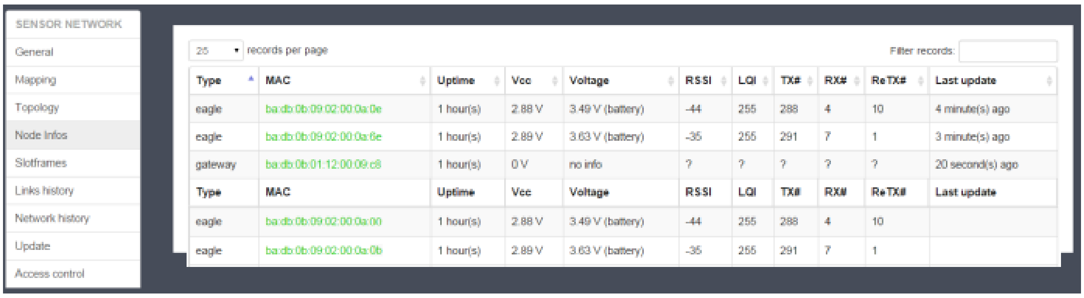


Figure 5.3.2. Sensor network settings [33]

The topology tab shows how the system is working. In this case, a green two lined connection between the sensor and the gateway is appreciated. The green color implies a good connection between the gateway and the transductor in both directions. This color could vary between red, orange and green, depending on the status of the connection.

It is also possible to tabulate the status and appreciate the operating conditions of the equipment:



Type	MAC	Uptime	Vcc	Voltage	RSSI	LQI	TX#	RX#	ReTX#	Last update
eagle	ba:db:0b:09:02:00:0a:0e	1 hour(s)	2.88 V	3.49 V (battery)	-44	255	288	4	10	4 minute(s) ago
eagle	ba:db:0b:09:02:00:0a:6e	1 hour(s)	2.89 V	3.63 V (battery)	-35	255	291	7	1	3 minute(s) ago
gateway	ba:db:0b:01:12:00:09:c8	1 hour(s)	0 V	no info	?	?	?	?	?	20 second(s) ago
Type	MAC	Uptime	Vcc	Voltage	RSSI	LQI	TX#	RX#	ReTX#	Last update
eagle	ba:db:0b:09:02:00:0a:00	1 hour(s)	2.88 V	3.49 V (battery)	-44	255	288	4	10	
eagle	ba:db:0b:09:02:00:0a:0b	1 hour(s)	2.89 V	3.63 V (battery)	-35	255	291	7	1	

Figure 5.3.3. Sensor network tabulated settings [33]

The quality of the signal is defined by the strength of the connection. This table Acoem provides specifies the quality of the signal depending on the Bode - Nyquist distribution [ANNEX IV]:

Signal Strength	Quality		Recommendations
-30 to -50 dBm	Excellent		
-50 to -60 dBm	Good		
-60 to -80 dBm	Fair		Install an expander
-80 to -90 dBm	Poor		Install an expander
< -90 dBm	Out of the topology		Substitute or install an expander

Table 5.3.1. Signal strength and quality [33]

Once all the connections and characteristics have been verified, it is necessary to update the system:

Figure 5.3.4. OneProd updating settings [33]

Having updated the interface, the first step to connect the cloud and the gateway is to link them:

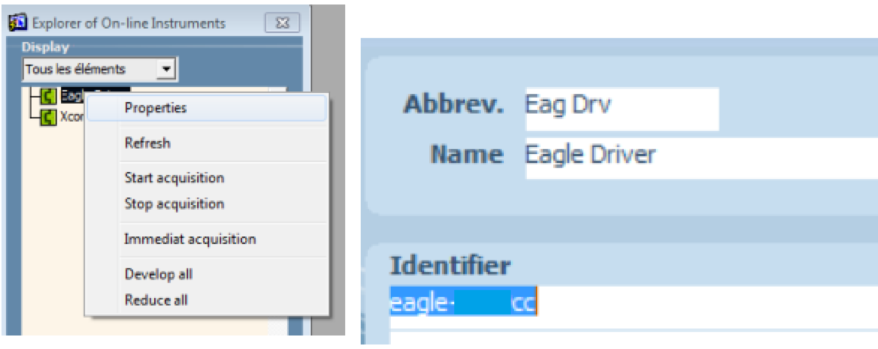


Figure 5.3.5. OneProd EAGLE properties [33]

The OneProd cloud [38] detects the EAGLE and it is only necessary to change the identifier to the one the gateway has written on its casing. If the connection has been correctly carried out, the interface will verify the status and guarantee the communication:

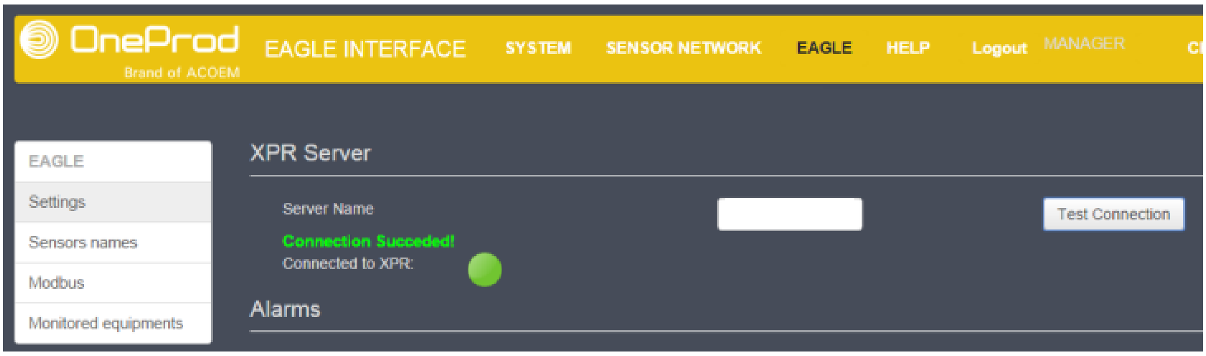


Figure 5.3.6. Gateway - accelerometers connection verification [33]

In order to monitor the machines, a modbus is created. Modbus is a channel that sends the signal to the cloud, in this case OneProd cloud, to study the results. The next step is to activate the master modbus, by using the manager credentials:

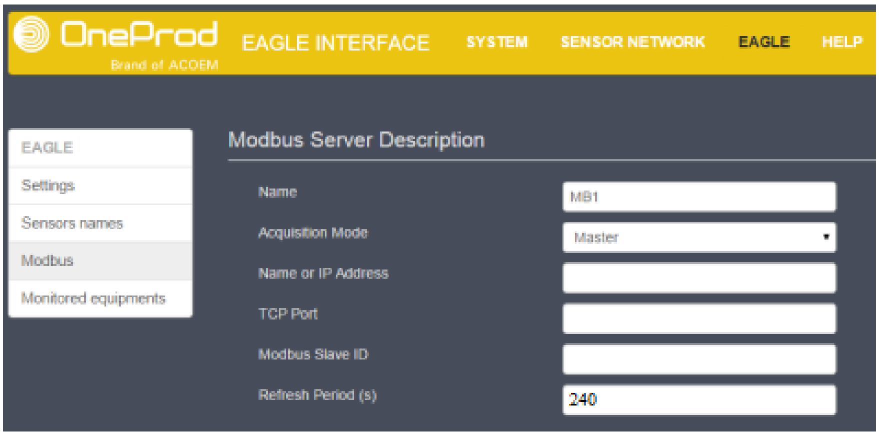


Figure 5.3.7. Modbus channel configuration [33]

It has been decided to apply a refreshing period of 240 seconds in order to reduce the uploading times of the accelerometers to increase the lifetime of the equipment.

By selecting the basics, it is possible to create the channel and to give access to the cloud. The first modbus created for the temperature will appear in the OneProd tree:

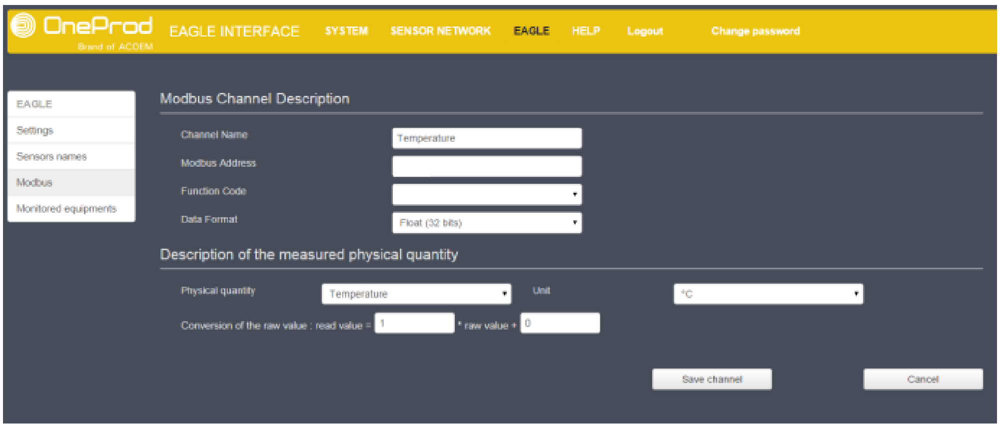


Figure 5.3.8. Modbus channel description [33]

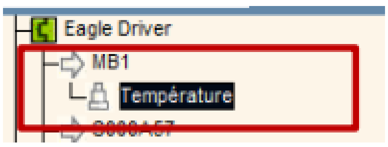


Figure 5.3.9. OneProd tree updated with the new channel [33]

For each parameter, the input must be changed to continuous, to update the collection automatically after a period of time (that will be configured after having set the rest of factors):

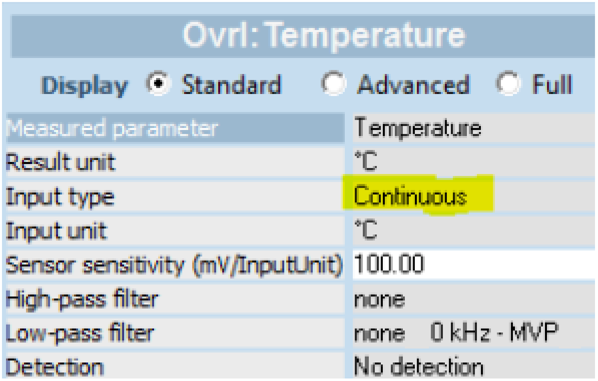


Figure 5.3.10. Temperature channel settings [33]

After having settled all the generic data of the first parameter, the time spectrums and the monitoring parameters can be displayed:

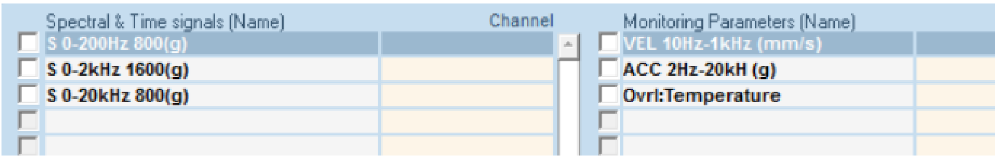


Figure 5.3.11. EAGLE parameters [33]

The High Frequency Filter (20kHz) is the only non required but given parameter of the EAGLE facilities. As the high frequency filter is not needed for the vibration study, it is eliminated from the monitoring parameters and replaced by two new filters: the low and medium frequency filters.

Before activating the channels of each parameter, it is a must to create the modbus for the rest of factors. The acceleration, the velocity and the time signal channels are created and linked.

The next step to monitor the vibrations of the centrifugal pump is to configure each parameter. As it has been explained for the temperature, each parameter appears in the OneProd tree and can be modified. The properties of each parameter are adapted for the project necessities:

Parameter	Frequency Filter	Spectrum
Measured Parameter	Both	Acceleration
Result Unit	Both	g
Medium Frequency Filter	None	2 kHz
Low Frequency Filter	None	200 Hz
Integration Step	Both	0 (Acc. 2)
Maximum Operating Frequency	LFF	10 kHz
	MFF	5 kHz
FFT Lines	LFF	3200 (g)
	MFF	1600 (g)
Averages	Changeable	3 - 5
Overlaps	LFF	75%
	MFF	50%

Table 5.3.2. Acceleration spectrum requirements

Parameter	Frequency Filter	Spectrum
Measured Parameter	Both	Velocity
Result Unit	Both	mm/s
Medium Frequency Filter	None	2 kHz
Low Frequency Filter	None	200 Hz
Integration Step	Both	1 (Vel. 1)
Maximum Operating Frequency	LFF	10 kHz
	MFF	5 kHz
FFT Lines	LFF	3200 (mm/s)
	MFF	1600 (mm/s)
Averages	Changeable	3 - 4
Overlaps	LFF	75%
	MFF	50%

Table 5.3.3. Velocity spectrum requirements

Parameter	Frequency Filter	Acceleration
Sampling frequency (Hz)	LFF	12800 - 25600
	MFF	2560 - 5120
	HFF	256 - 512
High Frequency Filter	None	None
Medium Frequency Filter	None	2 kHz
Low Frequency Filter	None	200 Hz
Number of Signal Points	LFF	8192 - 16384
	MFF	2048 - 4096
	HFF	512 - 1024

Table 5.3.4. Time signal requirements

The FFT lines, the frequency filters and the signal points have been selected in order to take the maximum advantage from the EAGLE system. Those factors come determined by the Acoem specifications and characteristics so, to leverage the equipment qualities, the most accurate settings have been selected.

Now it is possible to activate each parameter:

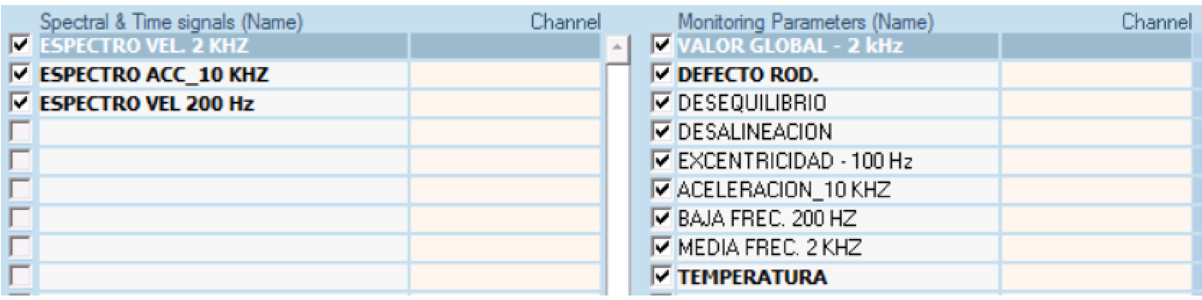


Figure 5.3.12. EAGLE active parameters [33]

The high frequency filter has been deactivated due to it having been previously modified for the time signal. This filter could be helpful for the waveform definition so it has been prepared in the time signal, but activating channels for the high frequency filters that, indeed, are not necessary, would reduce the lifetime of the collectors.

On the other side, the monitoring parameters desired for this study have been created:

- *DESEQUILIBRIO*: Refers to the unbalance of the bearings.
- *DESALINEACIÓN*: Refers to the bearing-shaft misalignment.
- *ACELERACIÓN*: Refers to the bearing vibration acceleration.
- *BAJA FREC.*: Refers to the pass filter of the envelope analysis. After reducing the frequency spectrum between 1 Hz and 200Hz, the oscillating velocity is studied.
- *Forma de onda*: Refers to the waveform. It has no values defined due to it is a graphic representation of the curve in the time domain. Each bearing has a waveform representation indicated by the question mark.
- *MEDIA FREC*: Refers to the pass filter of the envelope analysis. In this filter, the frequency range varies between 200 Hz and 2 kHz.
- *TEMPERATURA*: Refers to the bearing temperature. It only shows one value for bearing.
- *Kurtosis*: Refers to the Kurtosis distribution of the signal. Similarly to the waveform row, the question mark is the indicator of the diagram representation.
- *DEFECTO ROD.*: Refers to a mean value of the possibility of defect appearance. The value is based on the trend analysis evolution, taking into account the unbalance and misalignment results obtained at each bearing.
- *VALOR GLOBAL*: Refers to the mean velocity value of the whole frequency spectrum. It is a general indicator that helps to define if the defect may appear due to bearing condition or to over demanding circumstances.

To create the channels of each parameter it is necessary to define the alarm and stop levels of each parameter and give them an operating basis:

Indicator	Basis	Unit	Alarm Level	Stop Level
Unbalance	Velocity	mm/s	2,1	4,7
Misalignment	Velocity	mm/s	0,8	2,3
Acceleration	Acceleration	g	2,6	4,8
Low Frequency Filter	Velocity	mm/s	2	5,2
Waveform	Acceleration	g	Unexpected behavior	Symmetrical behavior
Medium Frequency Filter	Velocity	mm/s	1,5	2,1
Temperature	Temperature	°C	-5 / 65	-20 / 70
Kurtosis	Kurtosis Distribution	k Range	2,7 / 3,3	2,5 / 3,4
Bearing Defect	Waveform Defect	DEF Range	5,8	6,5
Mean Velocity Value	Velocity	mm/s	2,5	5,0

Table 5.3.5. Monitoring parameters and indicators specifications

All these specifications are detailed in the OneProd cloud editor for each indicator:

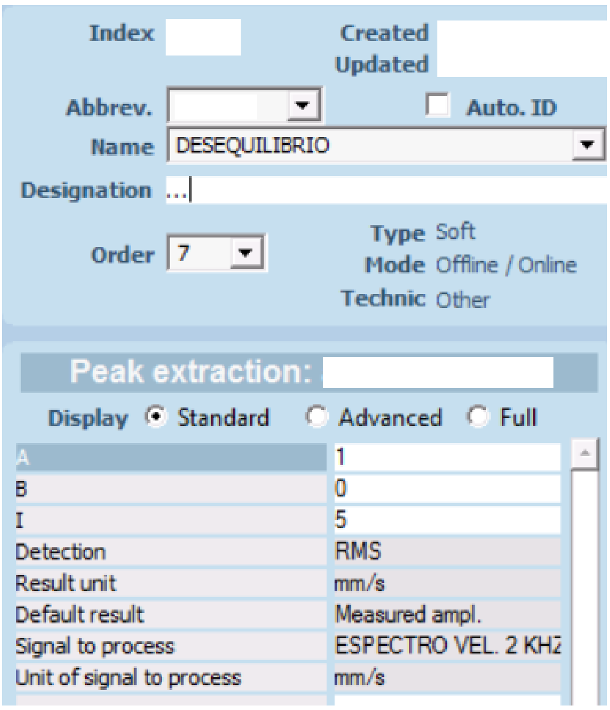


Figure 5.3.13. Unbalance modified properties [38]

And the alarm and stop levels are set:

Figure 5.3.14. Unbalance alarm and stop levels settings [38]

If it is desired to understand how the configuration has been completed, in the [ANNEX IV] the alarm and stop levels selections are described. This Annex includes the plots of each parameter from other stations from *SG* that have been helpful to fulfill the configuration.

After all the equipment configuration and connection completion, for each triaxial accelerometer, the X, Y and Z axes and the T (temperature) parameter appear. In the case of this project, the high frequency filters do not appear in the tree and, instead, the indicators introduced are appreciated in the supervision tab:

Figure 5.3.15. Monitoring parameters at the OneProd tree [38]

The next step after having properly configured and linked all the channels and parameters from the gateway to the cloud, it is time to program the operating conditions and the acquisition strategy.

In the OneProd cloud module, the tab is changed to the operating conditions:

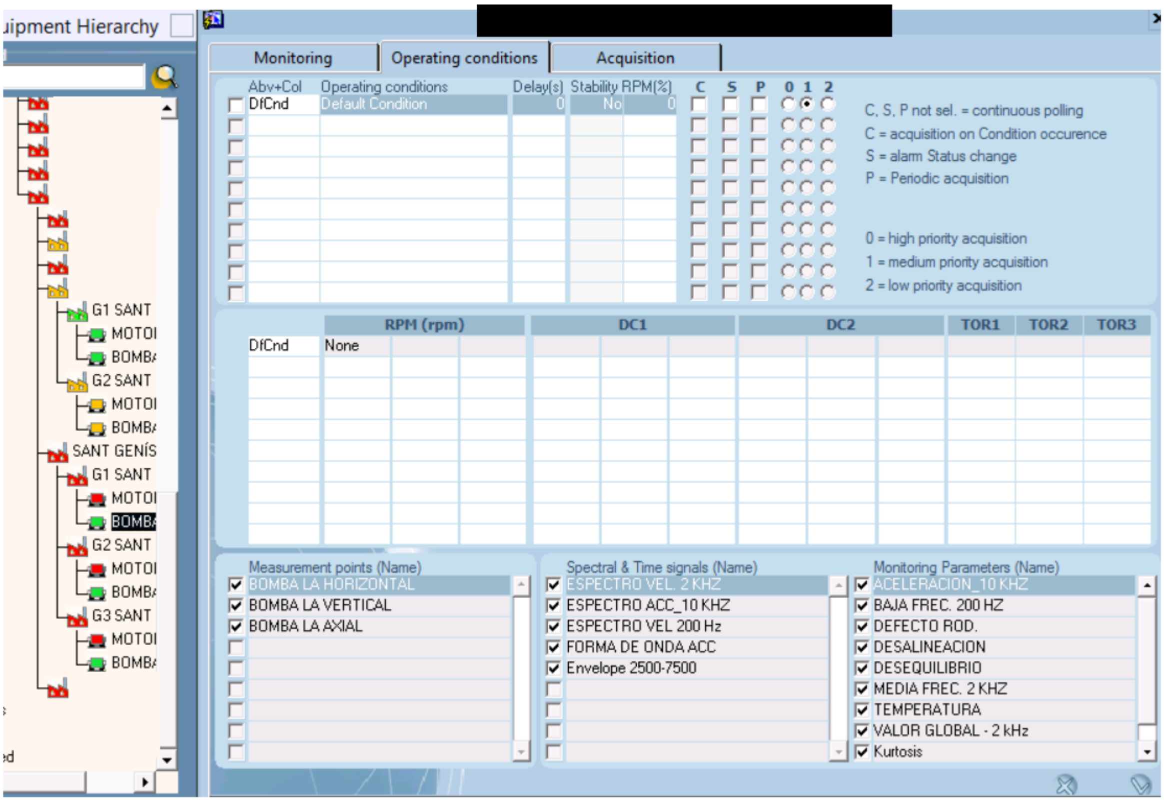


Figure 5.3.16. Operating conditions before the wireless adaptation [38]

As the *SG* terminals are fully wired monitored the monitoring parameters are not completed. The purpose is to receive an alarm in the event of finding unexpected values, so the S and P tools are marked. As it will be wireless monitored, it is not necessary to mark any priority acquisition due to the data will be automatically collected:

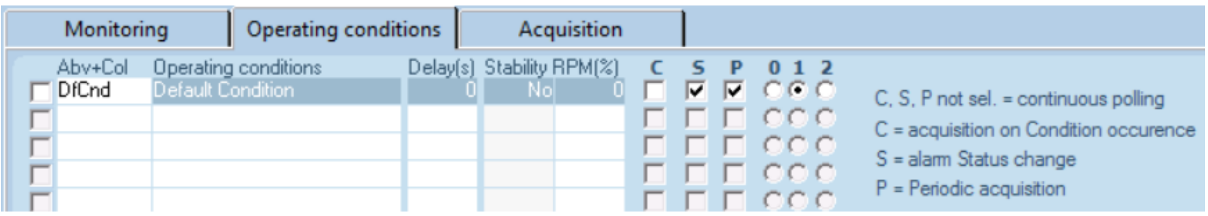


Figure 5.3.17. Operating conditions after the wireless adaptation [38]

The S mark implies a warning whenever the alarm level is exceeded while the P mark is for a periodic acquisition.

To configure the P mark it is necessary to determine an acquisition periodicity:

Figure 5.3.18. Acquisition strategies before the wireless adaptation [38]

First of all, the ON-LINE acquisition strategy is settled:

Figure 5.3.19. Online acquisition strategy settled on [38]

And then, the time periods are specified:

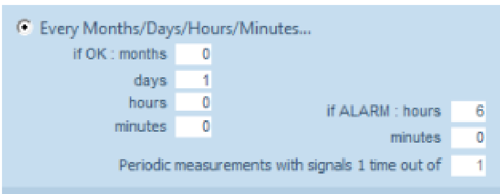


Figure 5.3.20. Acquisition strategies after the wireless adaptation [38]

After having configured all the parameters one by one, it is necessary to verify if the interface is correctly connected and to update again. If the update has been successful, it is time to monitor.

At this point, the configuration of the gateway and the equipment is completed and understanding how to use OneProd cloud tools in order to comprehend the condition of the machine follows.

6. DEFECT DIAGNOSIS

As it has been explained, *G3 SG II* is a station of Aigües de Barcelona, where other terminals have been monitored. One of the objectives of this report is to approximate the possible defects appearing at the *G3* during the future monitoring and, in order to successfully achieve results, the stations of *SG* sharing the same centrifugal pumps are compared.

The comparison is carried out by using the OneProd cloud. OneProd requires credentials that, after being introduced, accesses to the database of certain installations. In this case, the credentials used were provided by the principal director of this project, Mònica Egusquiza. Once entered in the database, all the collected information of the stations monitored and supervised by the director are available. This cloud resumes all the defect indicators and has multiple options to supervise them such as plotting the trend spectrums or describe the condition of the machines.

The left tree shows the installations the credentials give access to. As this project is centered on implementing a predictive maintenance model at *G3 SG II* station by studying the other *SG* terminals, the main purpose is to analyze them:

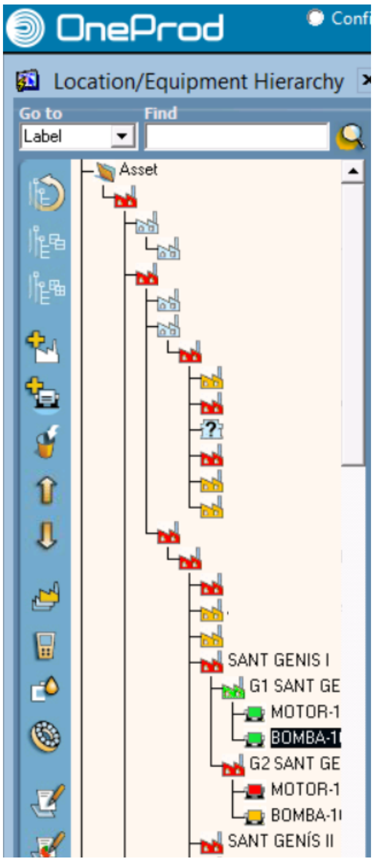


Figure 6.1. OneProd installation tree [38]

When selecting a terminal, the parameters evaluable can be chosen: Vibration process, diagnosis actions, data archives… In this report, the focus is to analyze the vibration indicators, so the parameter selected is Vibration process:

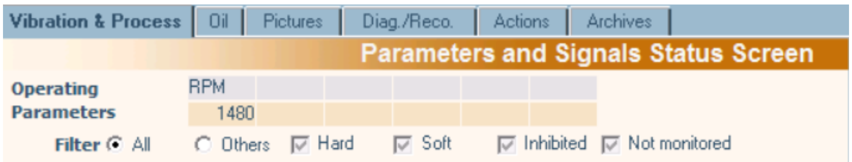


Figure 6.2. OneProd Vibration process indicators [38]

The condition indicators are divided between pump, motor and bearing. Each first bearing installed at the pump and the motor has three accelerometers installed controlling them, while the second bearings only have two:

PSS	BOMBA I	BOMBA I	BOMBA I	BOMBA I	BOMBA I
VALOR GLOBAL -	2.21	1.35	1.27	1.19	1.23
DEFECTO ROD.	3.09	3.05	3.01	2.96	2.81
DESEQUILIBRIO	1.04	0.692	0.490	0.112	0.401
DESALINEACION	0.425	0.060	0.099	0.192	0.089
ACELERACION_10 KH	0.332	0.276	0.398	0.360	0.320
BAJA FREC. 200 HZ	2.01	1.28	1.25	0.925	1.12
P-P Forma de onda		?			?
MEDIA FREC. 2 KHZ	0.984	0.387	0.351	0.651	0.508
TEMPERATURA	24.1			23.3	
Kurtosis		?			?

Figure 6.3. OneProd pump process indicators [38]

The first three columns represent the values collected by the three accelerometers installed in the first bearing of the pump and the last two columns are the results of the accelerometers mounted on the second bearing. The first and fourth columns are the horizontal accelerometers data, the second and fifth are the vertical results and the third is the axial value.

Each row represents the diagnosis indicators, which value varies in function of the bearing studied. For example, the third row represents the mean value of the unbalance for each bearing in a motor of the *G1 SG II* terminal:

PSS	MOTOR	MOTOR	MOTOR	MOTOR	MOTOR
VALOR GLOBAL -	10.3	4.05	3.84	3.45	0.974
DEFECTO ROD.	2.82	2.87	2.45	2.38	2.51
DESEQUILIBRIO	10.(	3.78	3.59	3.19	0.804
DESALINEACION	0.205	0.090	0.090	0.158	0.032
EXCENTRICIDAD - 1C	0.427	0.207	0.201	0.074	0.118
ACELERACION_10 KH	0.297	0.277	0.159	0.209	0.167
BAJA FREC. 200 HZ	10.3	3.90	3.73	3.27	0.938
MEDIA FREC. 2 KHZ	0.215	0.222	0.161	0.246	0.194

Figure 6.4. Unbalance by bearing at *G1 SG II* [38]

The green scheme implies that the alarm nor stop levels have been exceeded. Orange means alarm surpassed and red the stop of the machine. Each indicator can be plotted to see the evolution of that parameter:

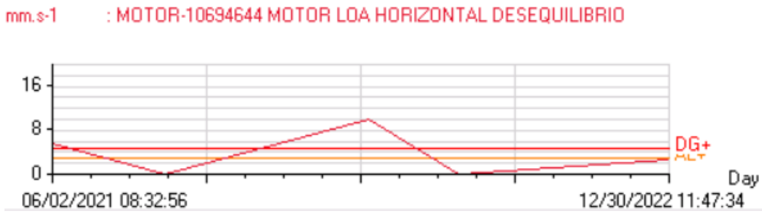


Figure 6.5. Unbalance of the motor first bearing trend plot at *G1 SG II* [38]

As appreciated, the alarm and stop levels of the machine were exceeded at some point. The fault got repaired, permitting the machine to operate in optimal conditions again. By seeing the graph, the error has persisted, at least, two times meaning that the defect must be a wear reason.

By having explained the OneProd uses with others similar to *G3* installations, the simulation of future defects could begin and, in order to advance, it is necessary to understand the data provided.

6.1. Condition indicators

In the following section, the indicators taken into account for diagnosing the defects detected during the vibratory analysis are explained. The safe thresholds of the stations of *SG* and the alarms exceeded are represented in order to clarify the diagnosis procedure. By using OneProd cloud [38], it is possible to evaluate multiple installations condition and plot the trend analysis of the status indicators, permitting the comparative between different terminals.

OneProd cloud offers a wide range of interest points of the machine, including the main indicators of each field. As the purpose of the project is to implement a predictive maintenance model for a centrifugal pump, the focus of the study resides in the vibration process data:

PSS	BOMBA I	BOMBA I	BOMBA I	BOMBA I	BOMBA I
VALOR GLOBAL –	2.21	1.35	1.27	1.19	1.23
DEFECTO ROD.	3.09	3.05	3.01	2.96	2.81
DESEQUILIBRIO	1.04	0.692	0.490	0.112	0.401
DESALINEACION	0.425	0.060	0.099	0.192	0.089
ACELERACION_10 KH	0.332	0.276	0.398	0.360	0.320
BAJA FREC. 200 HZ	2.01	1.28	1.25	0.925	1.12
P-P Forma de onda		?			?
MEDIA FREC. 2 KHZ	0.984	0.387	0.351	0.651	0.508
TEMPERATURA	24.1			23.3	
Kurtosis		?			?

Figure 6.1.1. Pump bearing condition indicators at *G1 SG I* [38]

In this image, all the principal bearing damage indicators of the *G1 SG I* branch are resumed. Each "*BOMBA*" refers to the accelerometers installed in the bearings of the pump impeller. The first column shows the data the Horizontal accelerometer has collected from the first bearing oscillation. The second and third column show the data obtained from that bearing, but in the Vertical and Axial directions, respectively. The last two columns are related to the bearing installed right after the impeller, showing the Horizontal and Vertical data the accelerometers have captured.

It is important to highlight that the impeller is not the only point where accelerometers are installed, centrifugal pumps require of another set of bearings in the motor:

PSS	MOTOR	MOTOR	MOTOR	MOTOR	MOTOR
VALOR GLOBAL –	1.63	0.950	1.63	0.820	1.54
DEFECTO ROD.	2.77	2.90	2.54	2.56	2.65
DESEQUILIBRIO	0.938	0.458	1.18	0.310	0.807
DESALINEACION	0.096	0.236	0.068	0.109	0.273
EXCENTRICIDAD - 1C	0.188	0.093	0.237	0.089	0.090
ACELERACION_10 KH	0.512	0.499	0.263	0.278	0.195
BAJA FREC. 200 HZ	1.58	0.945	1.48	0.840	1.46
MEDIA FREC. 2 KHZ	0.178	0.152	0.191	0.133	0.188
Kurtosis		?		?	
P-P Forma de onda		?		?	
TEMPERATURA	25.0		24.7		

Figure 6.1.2. Motor bearing condition indicators at *G1 SG I* [38]

The data resume works exactly the same than in the impeller case. Each "*MOTOR*" column refers to the motor bearings conditions. Once again, there are two bearings installed, the first one has three directed collectors and the second has the Vertical and Horizontal transductors.

The green background of each value implies that the indicator is under the alarm levels, so it is safe to operate. In the event of finding a value bypassing the alarm levels, the background is stained with orange. If the stop level is also exceeded, the rectangle turns red. For example, in the G2 *SG I* branch, the alarm and stop levels are exceeded:

PSS	MOTOR	MOTOR	MOTOR	MOTOR	MOTOR
VALOR GLOBAL –	4.69	1.84	4.12	1.49	3.13
DEFECTO ROD.	4.64	5.60	5.56	6.47	6.69
DESEQUILIBRIO	4.24	1.36	3.48	0.646	2.88
DESALINEACION	0.229	0.245	0.188	0.585	0.331
EXCENTRICIDAD - 1C	0.628	0.055	0.877	0.097	0.406
ACELERACION_10 KH	1.55	1.99	1.85	3.10	3.76
BAJA FREC. 200 HZ	4.64	1.80	4.05	1.47	3.11
MEDIA FREC. 2 KHZ	0.187	0.142	0.251	0.124	0.150
Kurtosis		?		?	
P-P Forma de onda		?		?	
TEMPERATURA	19.6		20.4		

Figure 6.1.3. Motor bearing condition indicators at *G2 SG I* [38]

Due to the variation of limits, it is important to predefine the thresholds of the parameters. Aigües de Barcelona has a very distinctive sample of ranges for each installation they have, that depends on the installation and the amount of turbomachines they manage. In the case of the SG branch, that includes "*G1 SG I*", "*G1 SG II*", "*G2 SG I*", "*G2 SG II*" and "*G3 SG II*"; the established ranges of safe operation are described in the [ANNEX IV].

After having commented the status indicators and how to determine their condition, it is possible to simulate the *G3 SG II* future defects.

6.1.1. Diagnosis procedure

In order to provide a proper diagnosis of the *G3 SG II*, there are three possible actions to apply, parameter by parameter, after seeing the vibration and process indicators results [39]:

1. The value does not exceed the alarm level: The value represented in the OneProd cloud display is the last point of the curve, meaning that it is possible that the trend plot is being unstable and the waveform has an unexpected behavior even if the last result is acceptable.

   With the purpose of preventing the exceedance of the alarm level, it is usual to refresh the indicators values and to follow the trend analysis evolution. If the trend analyses show common spectrums, it is implied that the bearing is working at good conditions but, if the trend analyses reflect a near future failure, the research for the defect progresses, looking for the reason for its emergence and how it could afflict the system.

2. The alarm level is exceeded: As previously commented, the indicator value could be over the alarm set for two reasons: a sudden curve variation or a continuous amplitude growth.
   - Usually, when the amplitude tends to increase, the failure is detected before it becomes an issue for the machine condition due to the unstoppable monitoring. This circumstance comes because of the bearing wear, being replaced or repaired.
   - When a sudden peak is displayed, the procedure becomes more complex. The most common answer is that the bearing or the shaft have been damaged implying, not only to detect the failure but to fastly solve it. This can be due to remains in the fluid or to an excessive demand on the bearings. It is usual to replace the afflicted parts, but the problem may persist and make the indicators surpass the stop level.

3. The stop level is surpassed: In this event, the machine is stopped and, if the defect has not yet been detected, examined. Once the damage has been repaired and the necessary parts have been replaced, the machine is activated again.

6.2. OneProd diagnosis graphs

As it has been explained before, the sensors collect data that can reproduce the diagram of the accelerations of the system through time. By applying the Fast Fourier Transformation, the domain of the plot can be changed from time to frequency domain, representing the acceleration of the system within a frequency bandwidth. In order to correctly interpret the resulting plot it is needed to comprehend the importance of each parameter and graphic outcoming. OneProd cloud [38] offers a diverse plot range, including:

1. Waveform plot:

As an example for the future diagnosis, here can be appreciated the waveform trend plot provided by OneProd for the unbalance of the second pump bearing at *G1 SG I*:

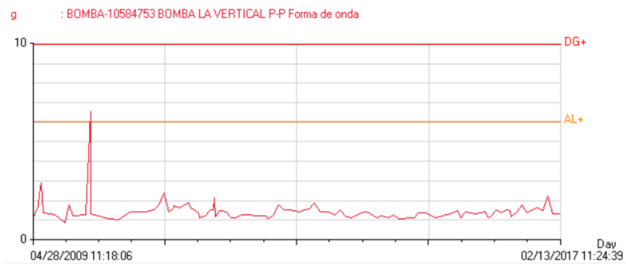


Figure 6.2.1. Unbalance of the second pump bearing at *G1 SG I* [38]

The signal is perceived as a sinusoidal wave. Its form can vary depending on the height of the peaks, the width of the curves and the symmetry of the periods. The parameters responsible for this definition are Kurtosis and Skewness, previously commented.

Kurtosis defines the distribution of the vibration amplitudes by flattering or sharpening the wave zeniths. In the event of detecting a high Kurtosis distribution, it is possible that there exist impacts, implying larger amplitudes. OneProd also provides examples for the Kurtosis and Skewness diagrams:

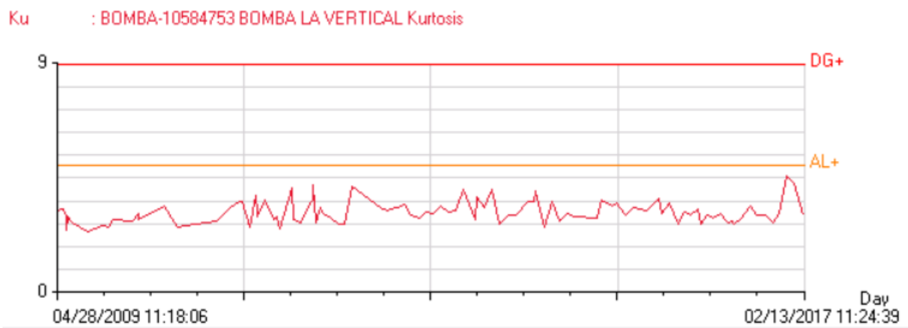


Figure 6.2.2. Kurtosis distribution of the second pump bearing at *G1 SG I* [38]

A normal Kurtosis result is 3 k. When the Kurtosis result is bigger than 3 is an excessive sharpness factor and if the distribution is larger than 3.3 is alarmant. On the other side, 2.7 k is an insufficient Kurtosis distribution, also being an alarm factor.

Skewness shows the symmetry of the vibration by deviating the wave to the left (negative distribution) or to the right (positive distribution). When the Skewness distribution is positive implies high amplitude vibrations while a negative distribution could indicate signal noise:

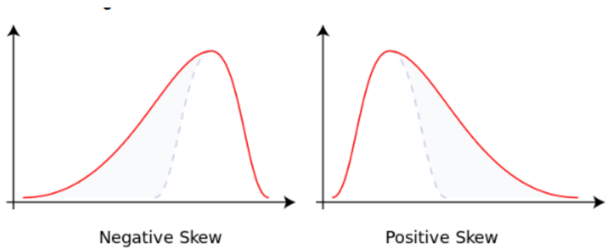


Figure 6.2.3. Skewness distribution of the second pump bearing at *G1 SG I* [38]

By comparing the Kurtosis and Skewness parameters with Figure 5.2.1., the distribution of the unbalance wave of the first motor bearing at *G1 SG I* can be calculated. This brief comparison is important to comprehend the signal behavior when studying the *G3 SG II* terminal.

2. Envelope plot:

The envelope plot is used in order to perform an envelope analysis. As an example for the future diagnosis, here can is displayed the envelope plot provided by OneProd for the unbalance of the second pump bearing at *G1 SG I*:

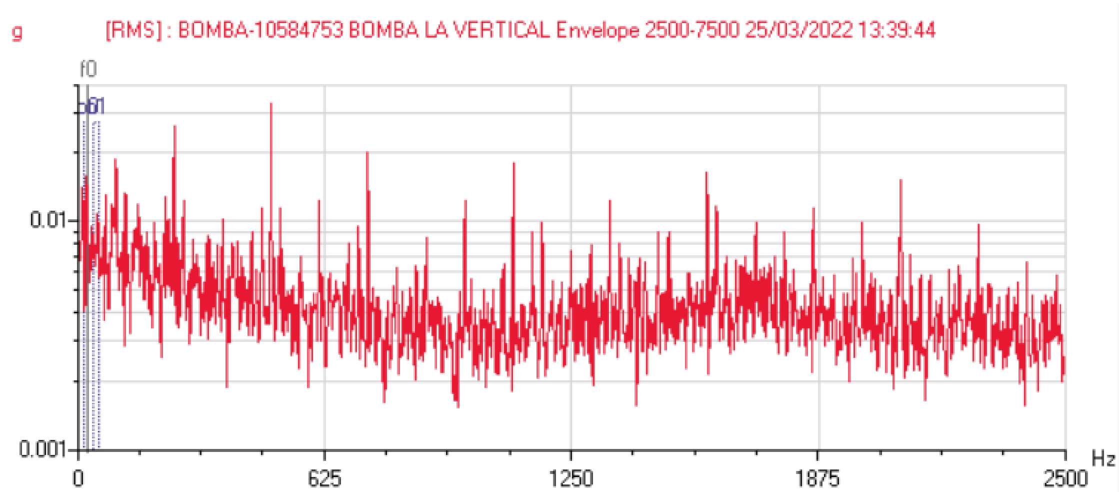


Figure 6.2.4. Envelope plot of the second pump bearing at *G1 SG I* [38]

3. FFT plot:

As an example for the future diagnosis, the FFT plot provided by OneProd for the unbalance of the second pump bearing at *G1 SG I* is presented:

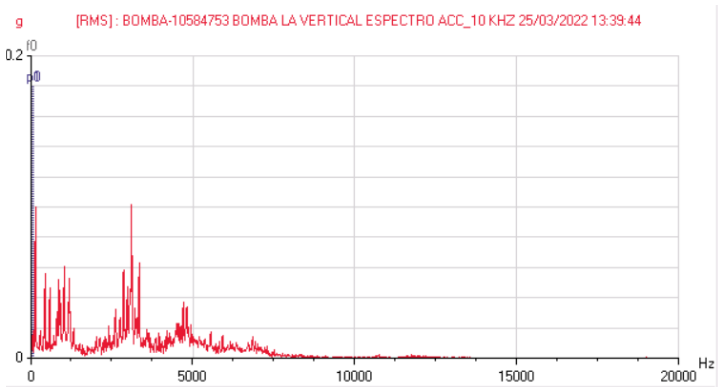


Figure 6.2.5. FFT plot of the second pump bearing at *G1 SG I* [38]

4. Cross channel orbits:

Cross-channel tracking is a basic measure of the gain and phase spectrums of each channel. By applying this method, the interdependence of the two signals can be determined, facilitating the identification of the vibrations source found in the equipment.

This procedure is mainly used in situations where it is not clear whether the detected vibration is caused by the pump subjected to study or by nearby machinery. In this event, the signal of both elements is compared with a two-channel analyzer.

The spectrum of each element is taken separately and then combined to appreciate if there is any overlap between peaks. If the signal crest from one of the plots coincides with another peak of the other channel, in terms of frequency, implies that the first element is involved in the vibration.

- Isolated vibration graphs:

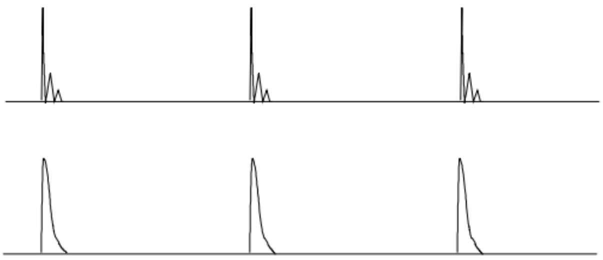


Figure 6.2.6. Self made simple recreation of two channels measures

- Combined channels:

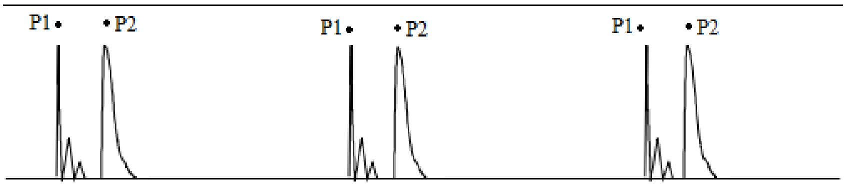


Figure 6.2.7. Self made simple recreation of two channels overimposed

If the devices are synchronized in the combined cross channel generation, the second element (to a lesser extent) also participates in the vibrations emitted. Find additional graphs in [ANNEX II].

6.2.1. Defect identification examples

Diagrams in the frequency domain are used to represent the accelerations based on the frequency at which the system is oscillating. The importance of determining the amplitudes of the wave in a frequency domain instead of the temporal domain is because natural frequencies and resonance are easily appreciated, leading to a more accurate diagnosis.

To clarify the plot's usual shape in contrast to the form of a defectuous system, some proposed examples are displayed where the acceleration units are g's ($9.81\ m/s^2$) and the frequency units are Hz's (Hertz). These examples provided show, in a very evident spectrum, how defects appear in the bearing condition indicators FFT plots:

- Gears diagrams depending on their status:

a) Good condition: Decreasing acceleration at each fundamental.

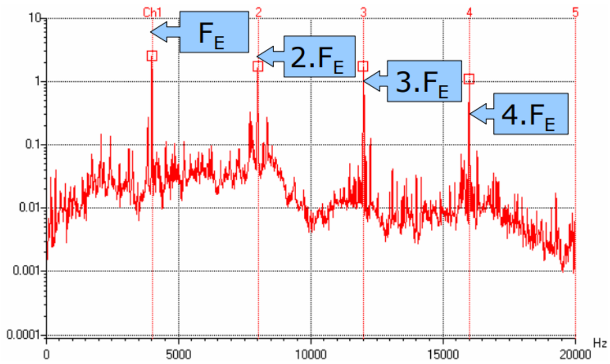


Figure 6.2.1.1. Good condition gear FFT diagram [11]

b) Beginning of a defect apparition: Distortion between the peaks and the curve.

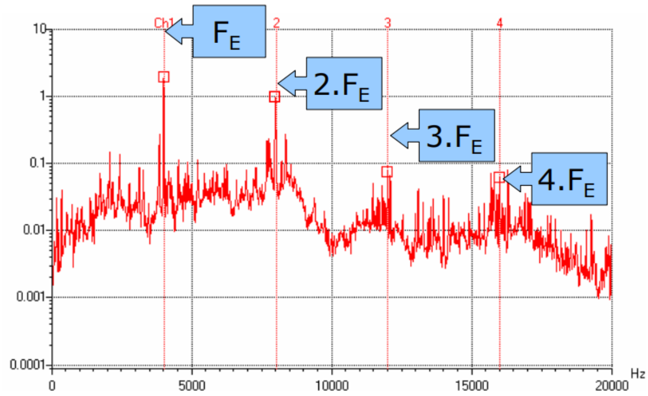


Figure 6.2.1.2. Defect beginning gear FFT diagram [11]

c) Weak kickback: The predominant acceleration is from the second natural frequency.

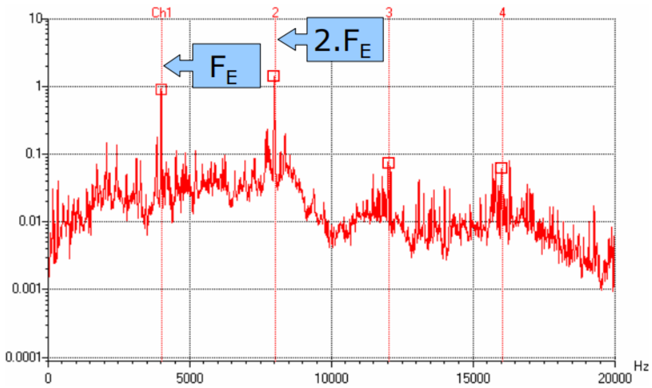


Figure 6.2.1.3. Insufficient kickback gear FFT diagram [11]

d) Excessive kickback: Large accelerations at each natural frequency.

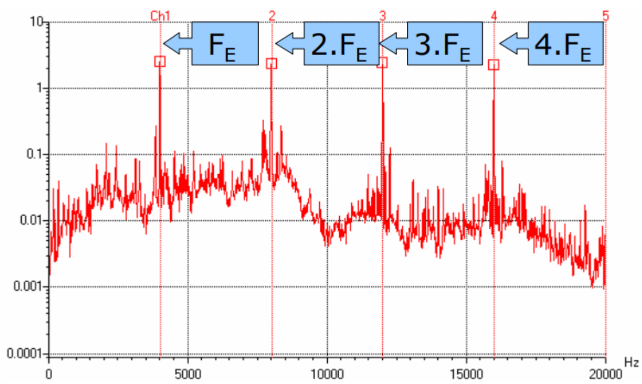


Figure 6.2.1.4. Excessive kickback gear FFT diagram [11]

e) Damaged teeth: Larger width of the curve with constant acceleration crests.

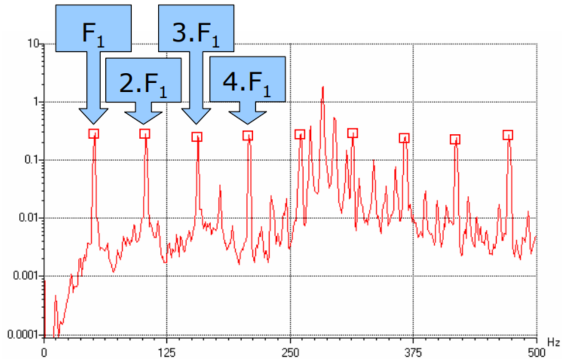


Figure 6.2.1.5. Broken teeth gear FFT diagram [11]

f) Advanced defects: The acceleration peaks vary and the curve width is fluctuant.

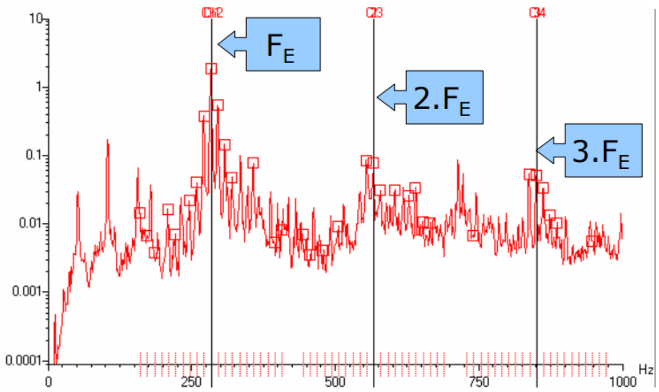


Figure 6.2.1.6. Advanced multiple defected gear FFT diagram [11]

- Bearings diagrams depending on their status:

a) Good condition: It is appreciated a soft unbalance in the decreasing acceleration zeniths due to the inevitable asymmetry of the machine.

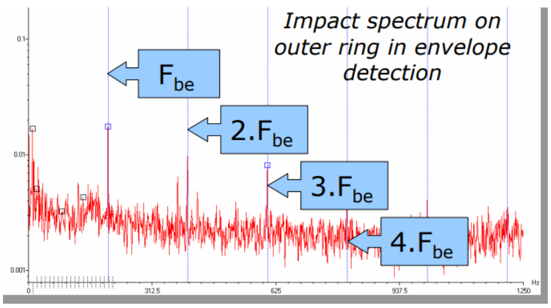


Figure 6.2.1.7. Good condition bearing FFT diagram [11]

b) Advanced unbalance: Similarly to the last example, the acceleration decreases but with larger width and sharper peaks.

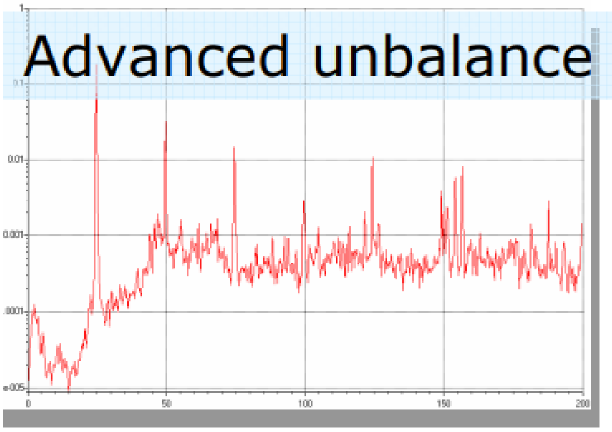


Figure 6.2.1.8. Unbalanced bearing FFT diagram [11]

c) Advanced misalignment: The unbalance behavior is overshadowed by the second natural frequency crest.

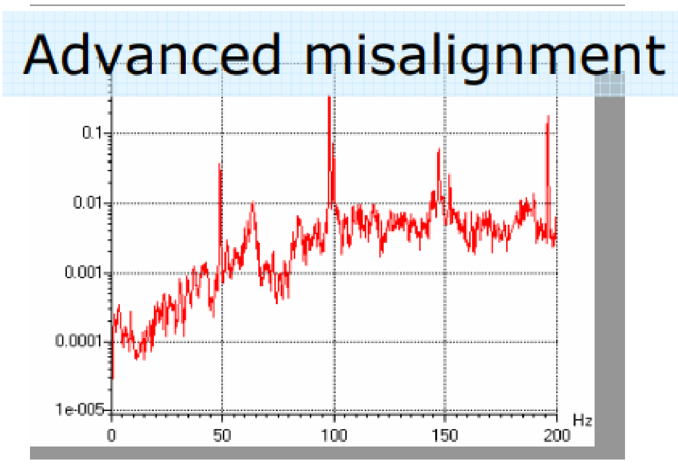


Figure 6.2.1.9. Misaligned bearing FFT diagram [11]

By showing these faults effects on FFT diagrams, the diagnosis of an incipient defect is easier to determine. Comprehending the possible faults actions it is simple to reduce the defects possibilities and outline which is the maintenance procedure.

6.3. Expected results of the monitoring

In this section the expected results of the future monitoring of the *G3 SG II* station are presented. These approximations of the behavior of the terminal find their basis on other *SG* stations and their operating condition when they used to be monitored, found in [ANNEX V].

As the Acoem EAGLE accelerometers have a lifetime of five years and the project duration is fifteen years, the results are divided into three stages, one for each set of sensors.

It is important to consider the alarm and stop levels decided in the [ANNEX IV]:

- Unbalance → $2.1 \ - \ 4.7\,mm/s$
- Misalignment → $0.8 \ - \ 2.3\,mm/s$
- Acceleration → $2.6 \ - \ 4.8\,g$
- Low Frequency Filter → $2.0 \ - \ 5.2\,mm/s$
- Mid Frequency Filter→ $1.5 \ - \ 2.1\,mm/s$
- Bearing Defect→ $5.8 \ - 6.5\,DEF$
- Global Value→ $2.5 \ - \ 5.0\,mm/s$
- Waveform→ Works different from the other indicators. The waveform is alarmant in the event of finding unexpected or unusual shapes of the time signal. The unexpected forms can be peaks appearing in non natural frequencies or extremely sharpened curves. The waveform is a stop factor in the event of finding symmetrical behaviors exceeding the Kurtosis sharpness.
- Kurtosis→ $2.7 \ / \ 3.3 \ - \ 2.5 \ / \ 3.4\,k$
- Temperature→ Following the bearings operating conditions: $-\ 5 \ / \ 65 \ - \ \ -\ 2 \ / \ 70\ °C$

These thresholds have been selected in function of the *SG* sets ranges. As the safe ranges have been defined by the lowest altered peaks of the *SG* terminals, it is important to consider that the alarm and stop levels are more prone to turn on.

The first column is the horizontal measure of the EAGLE at the first bearing, the second is the vertical measure and the third one is for the axial result. The fourth and fifth columns are the measures for the horizontal and vertical factors of the second bearing.

- First set: The unbalance of the machine is a very common defect that, eventually, will afflict the *G3 SG II* centrifugal pumps. For the first five years the defects expected focus on the first motor bearing, subjected to the closeness to the motor, the main vibration generator.

As it happened in the other *SG* stations, the motor bearings of the *G3* pumps are prone to be subjected to an exhaustive vibration that may produce the natural unbalance of the machines to anticipate. The unbalance only appears in the first and third measures of the accelerometer due to Lowara e-NSC is a bed mounted pump, implying very high vertical vibration impedance.

As the alarm levels are lower than in other similar stations, the medium frequency range alarm is activated in the first and second measures. It happens differently to other stations because of a more wide vibration amplitude produced by the altered unbalance.

As the unbalance in the horizontal axis is wider, the low frequency starts exceeding the stop levels helped by the unstoppable rotation of the shaft. It should not be an issue for the global condition of the machine, but could imply a future breakdown of the first motor bearing.

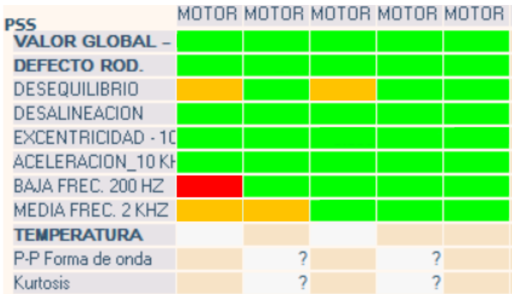


Figure 6.3.1. Expected results of the motor bearings condition for the first five years monitoring

On the other hand, the pump bearings should maintain a good behavior for the first five years due to being further from the vibrations origins. Expecting no cavitation nor turbulence in the fluid flux, the results should not exceed the alarm threshold.

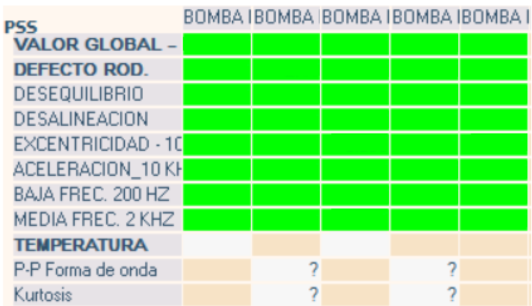


Figure 6.3.2. Expected results of the pump bearings condition for the first five years monitoring

- Second set: Contrary to the other *SG* stations, during the second monitoring the motor bearings should not be exceeding any threshold due to the maintenance applied when replacing the first accelerometers set. However, the pump should start showing the wear effects as a cause of the lack of maintenance during the procedure.

The motor first issues should have been repaired by reducing the temperature and friction of the bearings and the shaft. As the unbalance can be controlled with soft maintenance, the low and medium frequency ranges should be under the limits.

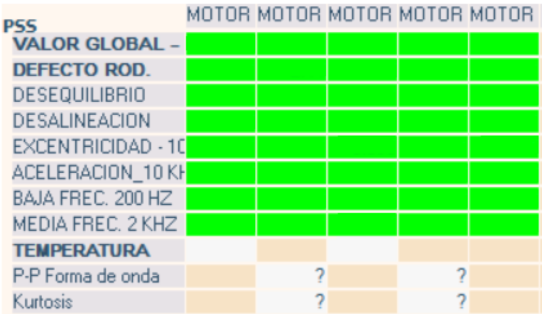


Figure 6.3.3. Expected results of the motor bearings condition for the second five years monitoring

The misalignment could be a logical answer to a constant effort during five years with no maintenance. The great conditions of the pump bearings during the first monitoring produced a false good impression for the second procedure. The wear in the motor - pump shaft connection may produce a soft misalignment in the first bearing.

As a consequence of the misalignment, the amplitude of the vibrations begins to exceed the safe thresholds, entering into a resonance motor - pump state. As it is the beginning of the resonance, it only afflicts the low frequency range. The vertical and horizontal misalignment produces the global condition to be affected, but not in an irreversible manner. As the misalignment has only afflicted the first bearing, the bearing defect condition is only determined by the low horizontal unbalance.

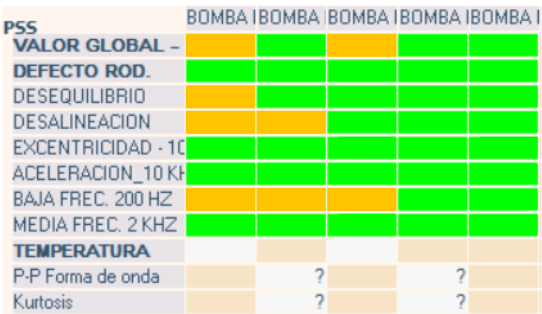


Figure 6.3.4. Expected results of the pump bearings condition for the second five years monitoring

- Third set: As previously mentioned, the pump bearings condition was not irreversible due to the soft misalignment but the motor bearings have been overdemanded.

The motor rotation has generated too much vibration in the shaft, making the bearings to be subjected to huge forces. The low frequency spectrum has found too high peaks over the third monitoring, afflicting the unbalance amplitudes. Even considering the vertical resistance of a bed mounted centrifugal pump, lack of maintenance has produced the exceedance of the stop threshold.

Even taking into account that the misalignment has not surpassed the alarm levels, the medium frequency safe range is lower than in other stations, implying an exceedance in the horizontal measure of the accelerometer of the first bearing.

Finally, the global condition of the bearings is expected to be defectuous. A fifteen year operation in a turbomachine is an overdemanding job for a bearing if it is not constantly maintained, resulting in being more logical to replace the bearing than maintaining it.

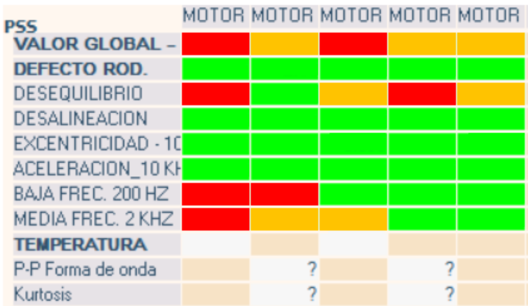


Figure 6.3.5. Expected results of the motor bearings condition for the third five years monitoring

After a proper maintenance in the second set, the pump bearings have recovered their initial status, reducing the friction with the shaft and lowering their temperature. But, even considering the pump bearings location, far from the pump - motor connection and from the rotation origin, they should be replaced. Operating for fifteen years exceeds the regulations established for the safety of a pump.

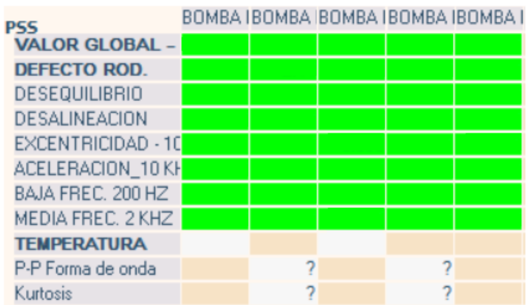


Figure 6.3.6. Expected results of the pump bearings condition for the third five years monitoring

After having presented the expected results of the monitoring of the *G3 SG II* station, it is important to mention that, in case of requiring the continuance of the monitoring, the bearings of the motor should be replaced and the pump ones could be maintained but it is recommended to replace them. Furthermore, cavitation would appear in the event of generating an excessive unbalance in the impeller area due to shaft shocks. After the appearance of the cavitation phenomena, turbulence could begin to affect the bearings and cause irreversible internal damage.

In the event of reaching this point, the connection between the motor - pump shaft should be repaired or even substituted. As the low frequency outranges come from unbalance defects, the shaft excessive vibration combined to the flux instability would produce the machine to be totally replaced. The shaft misalignment would appear due to the turbulence effect, reducing to almost zero the possibility of repairing the damages.

After the numerical expected results, the graphical behavior of the *G3* is presented:

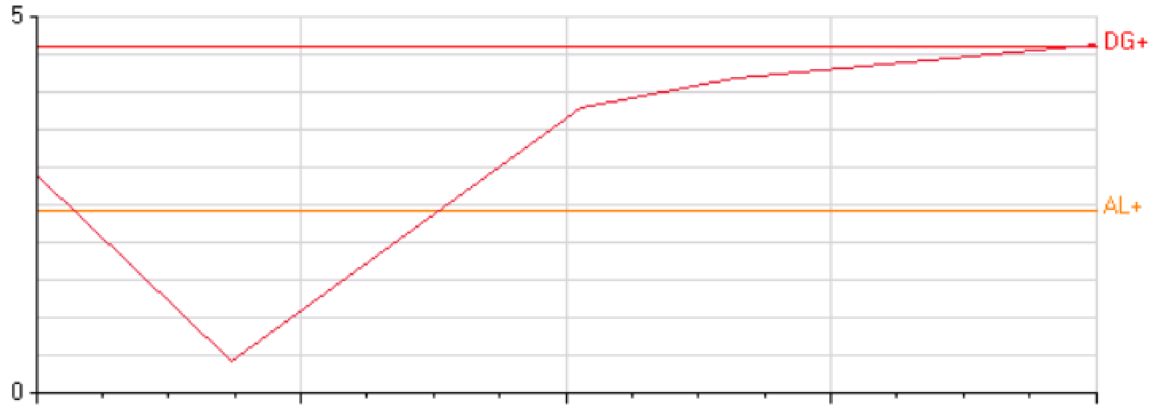


Figure 6.3.7. Expected results of the motor bearings

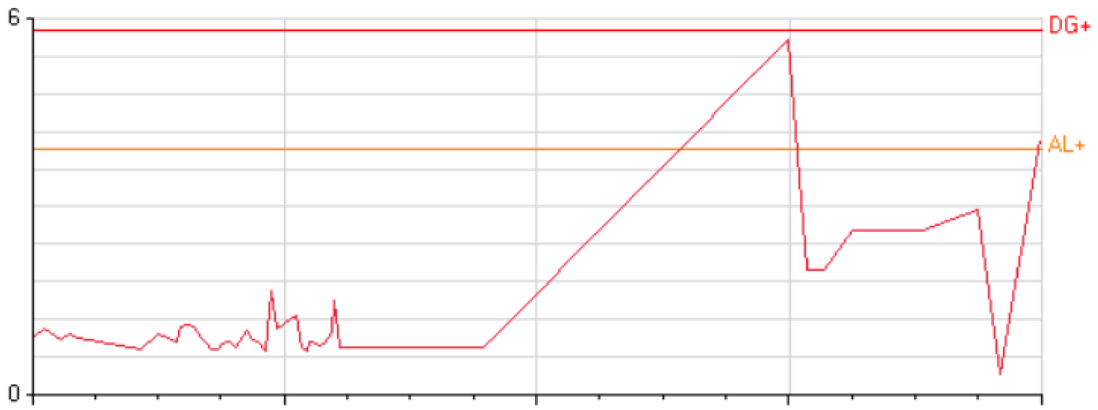


Figure 6.3.8. Expected results of the pump bearings

7. ENVIRONMENTAL IMPACT

Nowadays, the environmental impact of a project is a main factor to take into account when implementing it. Principally, the elements that describe this impact in this project are:

- Energetic consumption.
- Instrumentation and machinery production.
- Waste management.
- Emissions.
- Compliance of the regulations established for the project.

The energetic efficiency of the pump determines the consumption [40]:

$$DEC = \eta * P_N * T_d \quad \textbf{(Eq. 7.1.)}$$

Where "DEC" is the daily energetic consumption, "η" is the pump efficiency, "P_N" is the nominal potency and "T_d" is the amount of hours the pump is operating a day. Taking the data of the [ANNEX III] and assuming a useful life of fifteen years for the pump:

$$TEC = 0.875 * 177.5\, kW * 15\, y * 365\, d * 24\, h = 20408.0625\, kWh \quad \textbf{(Eq. 7.2.)}$$

Where "TEC" is the total energy consumption of the machine. To this consumption, it is important to add the acquisition system and the computer energetic consumptions:

$$TEC = 20408.0625\, kWh + 6570\, kWh + 12614.4\, kWh = 39592.46\, kWh \quad \textbf{(Eq. 7.3.)}$$

The production of the centrifugal pump, the accelerometer and the acquisition system, which includes the computer analyzing the data, imply the generation of wastes and their management. Residues can also be an important factor when minimizing the environmental impact of a project because they may not be recyclable. Waste management is a complex process that is closely related to the elements composition. Primarily, pumps are constituted by plastic and metallic parts that can be reutilized and repaired but, on the other hand, accelerometers and complex equipment such as computers and accelerometers have micro electronic systems that can be extremely difficult to renovate.

Waste management and element compositions are factors that can negatively affect the environmental impact of this project. In order to prevent the environmental damages, many standards and safety regulations are established to properly treat all the residues in addition to the standards of safety in [ANNEX I].

Finally, it is important to comprehend that the emissions of this project are not null, the computer connected and the operating pump are emissions generators [40]:

$$Emissions = P * T * C_{eq}$$ **(Eq. 7.4.)**

$$Pump = 177.5kW * 15y * 365d * 24h * 0,3426\frac{kg\,CO_2}{kWh} = 7990631.1kg\,CO_2$$ **(Eq. 7.5.)**

$$Computer = 0.048kW * 15\,y * 365\,d * 24h * 0,3426\frac{kg\,CO_2}{kWh} = 2160.85\,kgCO_2$$ **(Eq. 7.6.)**

$$A.S. = 0.051\,kW * 15\,y * 365\,d * 24\,h * 0,3426\frac{kg\,CO_2}{kWh} = 2295.9\,kg\,CO_2$$ **(Eq. 7.7.)**

$$Total\,Emissions = 7995087.85\,kg\,CO_2$$ **(Eq. 7.8.)**

By taking into account the computer and pump emissions and energy consumptions, it is appreciated that the impact is consistent but, if it is considered the fact that it is a fifteen year project with no additional effects and no waste generation, the impact regulation plans of the UE are accepted.

8. BUDGET

The budget for selecting, installing and configuring the wireless equipment is presented:

EQUIPMENT					
Item	Description	Units	Quantity	Mean Price by Unit	Total Price of the Item
Computer	MSi	uds.	1,00	1.210,92€	1.210,92€
Accelerometer	Acoem EAGLE	uds.	12,00	1.722,86€	20.674,32€
Acquisition System	EAGLE EDGE	uds.	1,00	1.241,13€	1.241,13€
				Total	23.126,37€
				IVA Included	27.982,91€

Table 8.1. Equipment costs

WORKERS					
Item	Description	Units	Quantity	Mean Price by Unit	Total Price of the Item
Supervisor	Mastered Engineer	h	800,00	20,74 €/h	16.592,00€
Student	Junior Engineer	h	40,00	12,30 €/h	492,00€
				Total	17.592,00€
				PIT Included	20.671,64€

Table 8.2. Workers costs

TOTAL COSTS				
Item	Units	Quantity	Mean Price by Unit	Total Price of the Item
Equipment	€	1,00	27.982,91€	27.982,91€
Workers	€	1,00	20.671,64€	20.671,64€
			Total	48.654,55€

Table 8.5. Total project cost

9. CONCLUSIONS

The selection and configuration of a wireless vibration acquisition system in order to implement an online monitoring for a centrifugal pump is a complex procedure, being a decision that determines the future of any predictive maintenance model.

During the research carried out to select and configure the vibration acquisition system, the importance of the vibration monitoring has come to light. Properly collecting and processing data dictates the future performance of the machine examined. Comprehending the status of the pump and diagnosing the potential defects is the only manner to guarantee its optimal condition.

By having built a theoretical background in such a complex engineering field as it is the vibration consequences in turbomachinery and the prevention of those, the instrumentation exploration has become the following step. Searching for the best wireless acquisition system between the diverse options many brands offer has resulted in the selection of the Acoem EAGLE. The results presented by the equipment comparative analysis are noteworthy, highlighting the perfect fit of the EAGLE sensors and gateway with the Lowara e-NSC pump model, collecting the necessary data to fulfill the condition indicators studied during the completion of this document.

The successful selection of the acquisition system together with the configuration procedure promises the future safety of the *G3* centrifugal pumps. Furthermore, the configuration methodology has been meticulously considered, studying the necessities of the Lowara device and taking into account the requirements of the vibration monitoring. The alarm and stop levels thresholds have been carefully obtained by following the *SG* stations behavior to guarantee the reliability of the collected data and maximize the lifetime of the centrifugal pump.

In addition to the main purposes, the comparative analysis conducted between other similar stations has presented the expected results of the wireless monitoring of the *G3* terminal, emphasizing the superiority of the wireless acquisition systems and facilitating the future maintenance of the pump. The wired monitoring demands very specific strategies, in addition to a constant updating procedure. Installing wireless equipment facilitates the monitoring, collecting more accurate and precise data and reducing installation and monitoring difficulties.

These project findings provide the wisest selection, configuration and location choice procedure of a wireless vibration acquisition system, enabling the future application of a continuous monitoring of the *G3* station and presenting a precise data collection.

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ANNEX I: REGULATIONS AND STANDARDS

The following ANNEX mentions the indispensable regulations a centrifugal pump subjected to a predictive maintenance model must satisfy, taken from [39]:

ISO 10816: Mechanical Vibrations - "Assessment of machine vibrations by measurements on non rotating parts". ISO 10816-1: General guidelines.

1. ISO 10816-2: Large land-based steam turbine generating sets in excess of 50 MW.
2. ISO 10816-3: Industrial machines with nominal power above 15kW and a nominal between 120 to 15000 rpm when measured in situ.
3. ISO 10816-4: Gas turbines driven sets excluding aircraft derivatives.
4. ISO 10816-5: Power generators and hydraulic pumps
5. ISO 10816-6: Reciprocating machines over 100 kw.

ISO 7919: Mechanical vibrations of non reciprocating machines, "Measurements on rotating shafts and assessment criteria". 1SO 7919-1: General guidelines.

1. ISO 7919-2: Large land-based steam turbine generating sets in excess of 50 MW.
2. ISO 7919-3 and ISO 7919-4: Coupled industrial machines. // Gas turbine sets.
3. ISO 7919-5: Machines sets in hydraulic power generating and pumping plants.

ISO 2954: Mechanical vibrations of rotating or reciprocating machines - Specifications for vibration intensity measuring instruments.

ISO 8579-2: Gear receiving code - Part 2: Determination of mechanical vibrations for gear transmission during receiving tests.

ISO 14694: Industrial fans - Specifications for the quality of balancing and vibration levels.

API STANDARD 610: Centrifugal Pumps for Petroleum, Heavy Duty Chemical and Gas Industry Services - 1994.

API STANDARD 611 : General Purpose Steam Turbines for Petroleum, Chemical, and Gas Industry Services - 1994.

API STANDARD 612: Special Purpose Steam Turbines for Petroleum, Chemical, and Gas Industry Services - Jun.1995.

API STANDARD 613: Special Purpose Gear Units for Petroleum, chemical, and Gas Industry Services - Jun.1995.

API STANDARD 616: Gas Turbines for Petroleum, Chemical, and Gas Industry Services - Aug.1998.

API STANDARD 617: Compressors for Petroleum, Chemical, and Gas Industries - Feb.1995.

API STANDARD 618: Reciprocating Compressors for Petroleum, Chemical, and Gas Industries.

API STANDARD 619: Rotary-Type Positive Displacement compressors for Petroleum, Chemical, and Gas Industry services - 1995.

API STANDARD 670: Machinery Protection Systems - Dec. 2000.

API STANDARD 671: Special-Purpose Couplings for Petroleum, Chemical, and Gas Industry Service - Oct.1998.

API STANDARD 672: Packaged, Integrally Geared Centrifugal Plant and Instrument Air Compressors for General Refinery Service.

API STANDARD 673: Special-Purpose Centrifugal Fans for general Refinery Service - Jan.1982.

API STANDARD 674: Positive Displacement Pumps -Reciprocating.

API STANDARD 675: Positive Displacement Pumps - Controlled Volume.

API STANDARD 676: Positive Displacement Pumps - Rotary.

API STANDARD 677: General-Purpose Gear Units for General Refinery Service.

API STANDARD 678: Accelerometer-Based Vibration Monitoring system.

API STANDARD 684: Tutorial on the API Standard Paragraphs Covering Rotor Dynamics and Balancing: "An introduction to Lateral Critical and Train Torsional Analysis and Rotor Balancing".

ANNEX II: ADDITIONAL INDICATORS BODE AND NYQUIST

Bode and Nyquist diagrams [41] are presented as an additional tool to determine the stability and noise of a signal. They can be represented with OneProd but are not required for the implementation of this project but may be necessary for a deep vibration analysis.

These analyzes directly indicate the stability and frequency response of a system. The frequency response is understood as the relationship between the noise caused by the vibration and the frequency associated with the loudness level (high or low).

The balance of a system afflicts the machine oscillation. When instabilities appear in a set, it is not possible for the system to get back to its equilibrium status, facilitating the appearance of damages.

- Bode diagram:

A Bode plot consists of two graphs, one shows the magnitude of the sound in decibels, also known as gain, and the second one displays the wave phase.

The gain representation presents if the system amplifies a system signal by relating the amplitudes of the input and output signals. It is displayed as a function of the frequency in a logarithmic scale.

The phase determines if there is any delay between the output and input signals. It is the difference of the input and output signals amplitudes and is represented in radians or degrees.

By applying the Bode graph it is possible to investigate the phase margin, which defines the minimum wave angle for 0 dB system gain, and the gain margin, which provides the value that should be added to the gain to reach 0 dB when the phase is -180°.

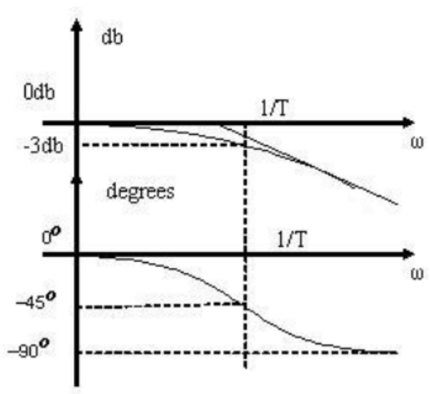

Figure II.1. Bode plot complete representation [42]

- Nyquist diagram:

In contrast to Bode's diagram, Nyquist proposes a graphic depiction of a system's frequency response in the complex plane. The curve of this method illustrates how the system reacts to various frequencies, helping to understand how a system gain and phase interact with their poles and zeros in the complex plane depending on the frequency.

Poles are the frequencies at which the response in frequency of the system becomes undefined or infinite and zeros are the points where the response results in zero. The real part of the response is represented in the horizontal axis and the imaginary one is plotted in the vertical axis.

To construct this diagram it is necessary to trace a curve upon the resulting frequency response of the system as the frequency varies from zero to infinite, is known as the Nyquist curve.

In this plot, the stability is studied by observing the Nyquist curve location, and comparing it with the critical point. The critical point is defined as (-1,0) because it represents the frequency where the system gain is equal to 1 dB and the phase is 180 degrees.

When tracing the curve, there are only three possibilities: The curve is traced clockwise around the critical point, implying balance. In the event of tracing it counterclockwise, the system is supposed to be unbalanced. The third chance is that the Nyquist curve crosses the critical point, meaning that the system is marginally stable, being the only spot where the system is neither stable nor unstable.

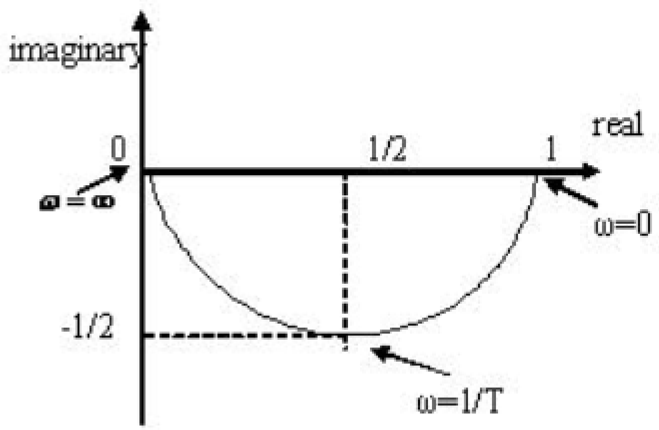

Figure II.2. Nyquist diagram simple representation [42]

ANNEX III: EQUIPMENT SPECIFICATIONS

Lowara e-NSC is the suction centrifugal pump in the *SG* stations. The supplier, *Xylem*, recommends reducing the operating velocity to the 50% of its maximum to achieve 87.5% of energetic efficiency. Usually, this type of pump is destined to the water transport, energy distribution, firefighting and other industrial utilities. The specifications of this machine are:

Capacities	Ranges
Flow delivery	1800 m3/h
Maximum head	160 m
Operating power	250 W - 355 kW
Maximum pressure	16 bar
Temperature range of the fluid	-25°C - 140°C
Motor range	E3<
Protection state	IP55
Motor voltage frequency	50 W - 60 kW

Table III.1. Lowara e-NSC characteristics [43]

Figure III.1. Lowara e-NSC centrifugal pump and motor [43]

Sensor Capacities	Ranges
Transmission interval	Configurable to a minimum of 10 minutes
Frequency range	2 Hz - 10 kHz in the Z axis and 0 Hz - 1 kHz in the X and Y axes
Amplitude range	50 g in the Z axis and 16 g in the X and Y axes
Sampling frequency	18.5 kHz - 62.5 kHz
Temperature measurement and storage range	-20°C - 85°C
Size	68mm x 53.4mm
Weight	199.5g
Ingress protection class	IP67
Shock Limit	5000 g peak
Power	6 x 3.6V 1/2 AA Li-SOCl batteries
Battery lifetime	1 - 2 years
AD Conversion	24 bit
Wireless Communication (sensor to gateway)	
Radio Frequency	2.4 GHz ISM band according to IEEE 802.15.1
Range	Up to 100 meters, depending on environment
Gateway Capacities	
AC main power	AC input 85-264 VAC, 0.35A/115V, 0.25A / 230V, 47-63 Hz
Power-Over-Ethernet	Compliant with IEEE 802.3af
WIFI	IEEE 802.11 ac/a/b/g/n
WIFI Security	WPA/WPA2
Ethernet	10/100/1000 MBits/s
Ingress protection class	IP67
Temperature operation	-20°C to 60°C
Temperature storage	-40°C to 80°C

Table III.2. Fluke accelerometer and acquisition system specifications [33]

Sensor Capacities	Ranges
Transmission interval	Configurable to a minimum of 10 minutes
Frequency range	10 Hz - 10 kHz in the Z axis and 0 Hz - 1 kHz in the X and Y axes
Amplitude range	50 g in the Z axis
Sampling frequency	50 Hz - 10 kHz
Temperature measurement and storage range	-40°C - 85°C
Size	80mm x 33.7mm
Weight	142g
Ingress protection class	IP69K
Shock Limit	5000 g peak
Power	24 V DC or Power over ethernet
Battery lifetime	4 - 8 years
AD Conversion	128 bit
Wireless Communication (sensor to gateway)	
Radio Frequency	Mira Mesh low energy mesh radio network (2.4 GHz ISM band)
Range	10 - 30 m
Gateway Capacities	
AC main power	Industrial range 24 V DC or Power Over Ethernet
Power-Over-Ethernet	Compliant with IEEE 802.3af
WIFI	802.11 a/b/g/n/ac 2.4 - 5 GHz
WIFI Security	WPA2
Ethernet	10/100/1000 MBits/s
Ingress protection class	IP65
Temperature operation	-20°C to 60°C
Temperature storage	-40°C to 60°C

Table III.3. SKF accelerometer and acquisition system specifications [34]

Sensor Capacities	Ranges
Transmission interval	Smart Interval
Frequency range	10 Hz - 15 kHz in the Z axis and 0 Hz - 16kHz in the X and Y axes
Amplitude range	50 g peak 24 bits
Sampling frequency	256 Hz - 51.2 kHz
Temperature measurement and storage range	-20°C - 70°C
Size	48mm x 113mm
Weight	403g
Ingress protection class	IP67
Shock Limit	500 - 5000 g peak
Power	48 V / 0.3 A DC or Power over ethernet
Battery lifetime	5 years
AD Conversion	24 bit
Wireless Communication (sensor to gateway)	
Radio Frequency	2.4 GHz ISM band
Range	Up to 100 m
Gateway Capacities	
AC main power	48 V DC / 0.3 A or Power Over Ethernet
IT and Networks	TCP/IP. HTTPS, DHCP
WIFI	802.11 a/b/g/n/ac 2.4 - 5 GHz
WIFI Security	WPA2
Ethernet	10/100 MBits/s Base
Ingress protection class	IP67 and IP68
Temperature operation	-20°C to 60°C
Temperature storage	-20°C to 60°C

Table III.4. Acoem EAGLE accelerometer and acquisition system specifications [20]

Sensor Capacities	Ranges
Power	24 V / 2.2 mA / 0.75 mW DC
Frequency range	4 - 2300 Hz
AD Conversion	16 bit
Sampling frequency	61.4 kHz
Temperature measurement and storage range	-20°C - 85°C
Size	203mm x 102mm x 152mm
Weight	1290g
Ingress protection class	IP66

Table III.5. PCB accelerometer and acquisition system specifications [35]

ANNEX IV: ALARM AND STOP LEVELS SELECTION

In the following ANNEX can be found the alarm and stop thresholds of the bearings at each installation of the *SG* set. The plots shown are taken from the motor/rotor bearing of each complex, due to not being possible to illustrate all the bearings limits. By comparing the following plots of the ranges of other terminals that share the same type of centrifugal pump with the *G3*, the alarm and stop levels have been selected as:

- Unbalance → $2.1 \; - \; 4.7 \; mm/s$
- Misalignment → $0.8 \; - \; 2.3 \; mm/s$
- Acceleration → $2.6 \; - \; 4.8 \; g$
- Low Frequency Filter → $2.0 \; - \; 5.2 \; mm/s$
- Mid Frequency Filter→ $1.5 \; - \; 2.1 \; mm/s$
- Bearing Defect→ $5.8 \; - 6.5 \; DEF$
- Global Value→ $2.5 \; - \; 5.0 \; mm/s$
- Waveform→ Works different from the other indicators. The waveform is alarmant in the event of finding unexpected or unusual shapes of the time signal. The unexpected forms can be peaks appearing in non natural frequencies or extremely sharpened curves. The waveform is a stop factor in the event of finding symmetrical behaviors exceeding the Kurtosis sharpness.
- Kurtosis→ $2.7 \; / \; 3.3 \; - \; 2.5 \; / \; 3.4 \; k$
- Temperature→ Following the bearings operating conditions: $-\;5 \; / \; 65 \; - \; -\;2 \; / \; 70\;°C$

These thresholds have been selected in function of the *SG* sets ranges. The lowest alarm peak collected at each factor determines the alarm level and the lowest stop apex is the stop level.

- ***DESEQUILIBRIO* or Unbalance:**

1. *G1 SG I*:

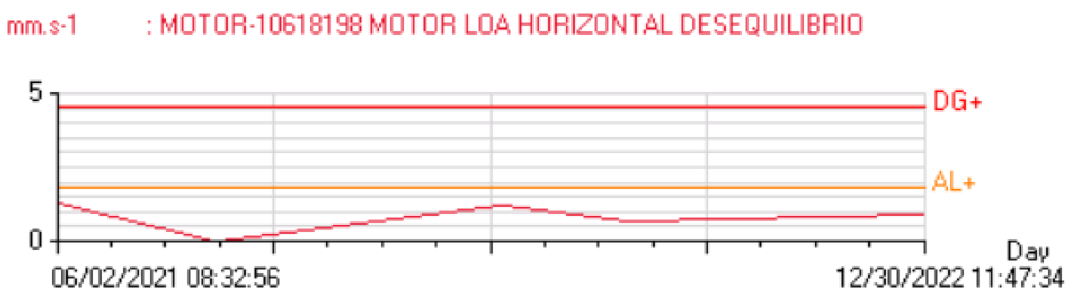

Figure IV.1. Motor bearing unbalance compared to the alarm and stop levels at G1I [38]

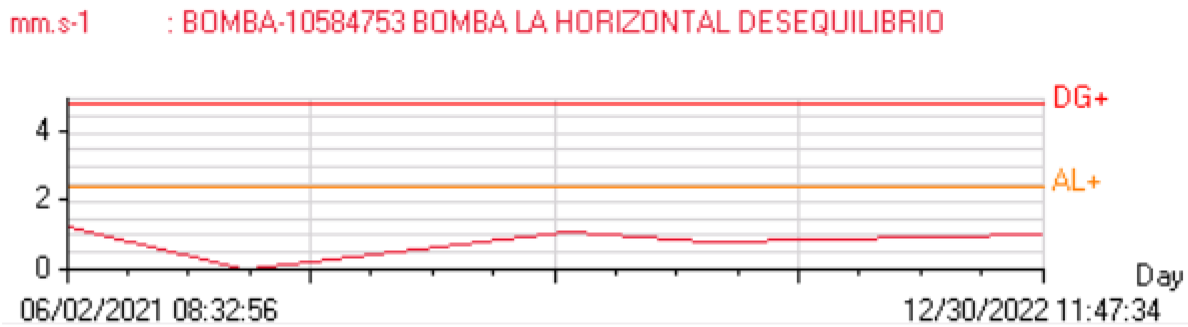

Figure IV.2. Pump bearing unbalance compared to the alarm and stop levels at G1I [38]

2. *G2 SG I*:

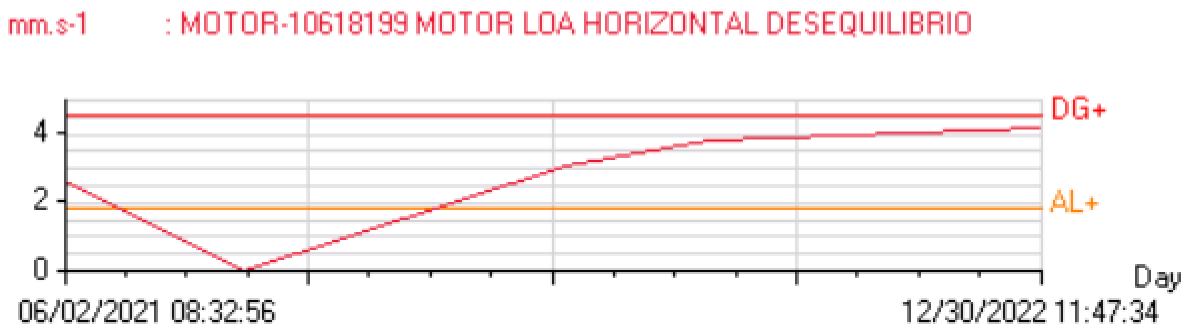

Figure IV.3. Motor bearing unbalance compared to the alarm and stop levels at G2I [38]

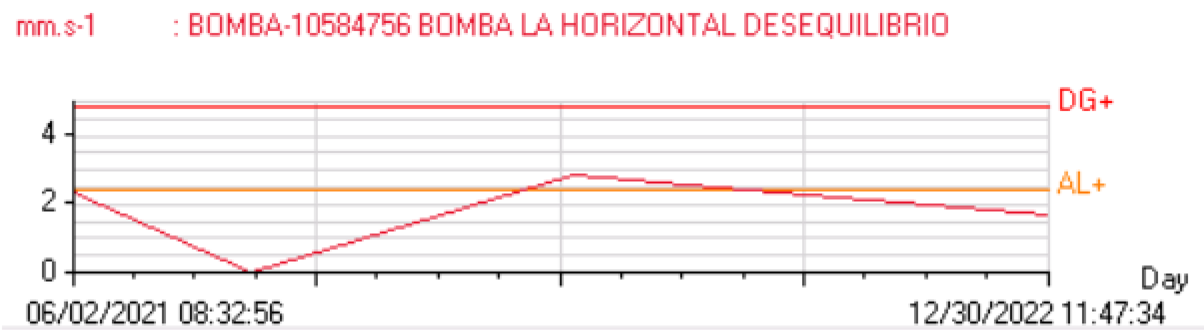

Figure IV.4. Pump bearing unbalance compared to the alarm and stop levels at G2I [38]

3. *G1 SG II*:

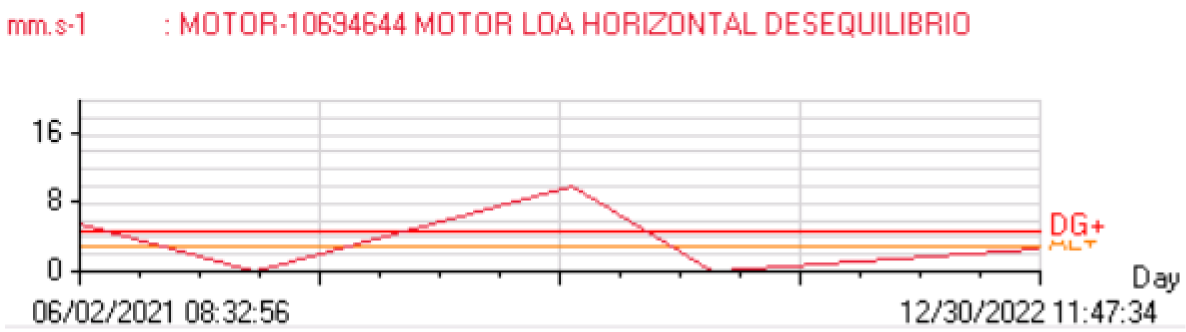

Figure IV.5. Motor bearing unbalance compared to the alarm and stop levels at G1II [38]

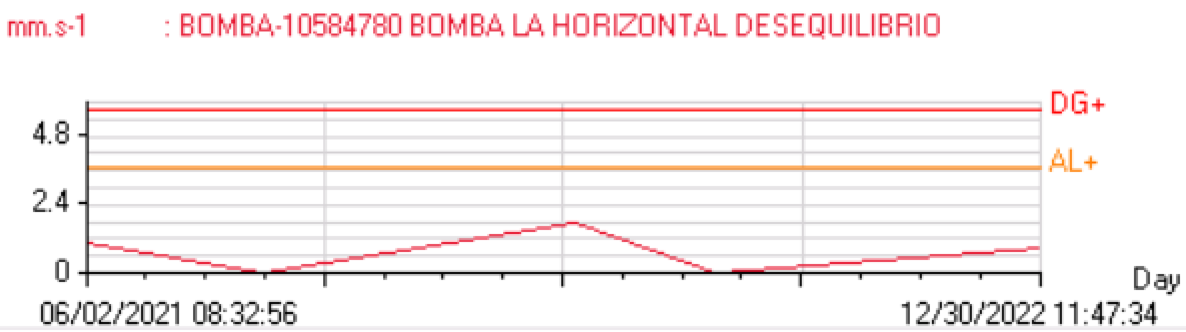

Figure IV.6. Pump bearing unbalance compared to the alarm and stop levels at G1II [38]

4. *G2 SG II*:

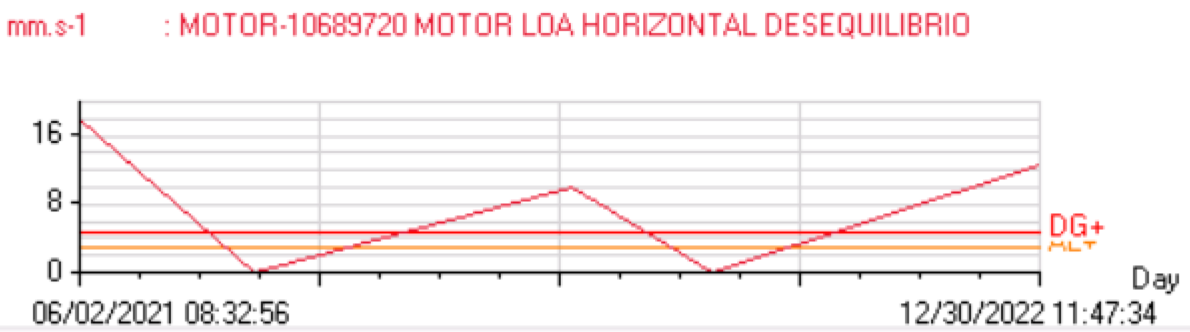

Figure IV.7. Motor bearing unbalance compared to the alarm and stop levels at G2II [38]

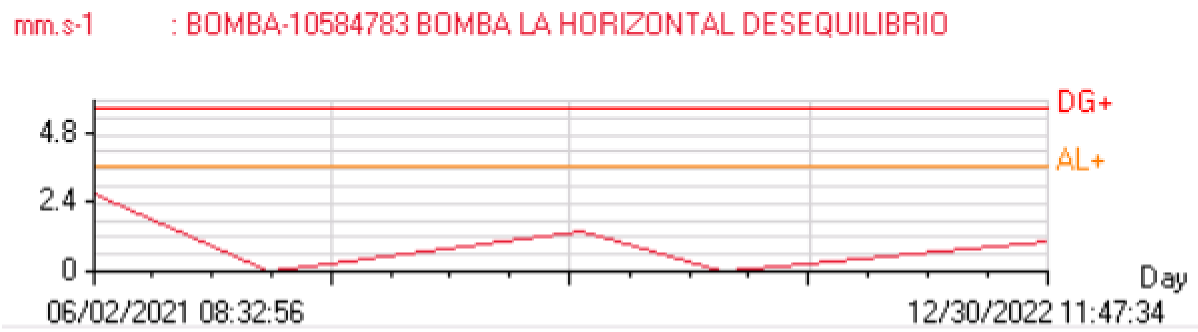

Figure IV.8. Pump bearing unbalance compared to the alarm and stop levels at G2II [38]

- ***DESALINEACIÓN*** **or Misalignment:**

1. *G1 SG I*:

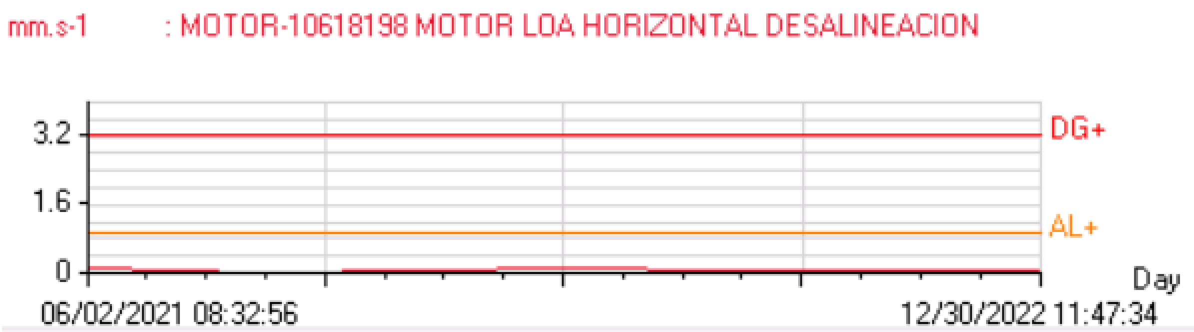

Figure IV.9. Motor bearing misalignment compared to the alarm and stop levels at G1I [38]

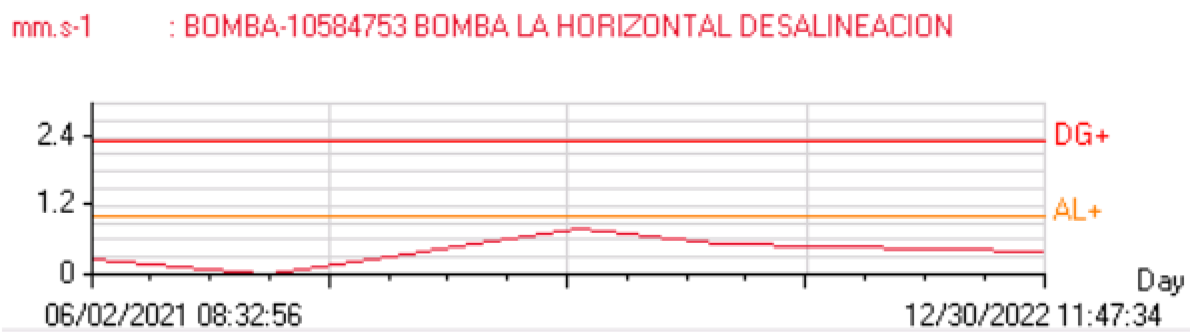

Figure IV.10. Pump bearing misalignment compared to the alarm and stop levels at G1I [38]

2. *G2 SG I*:

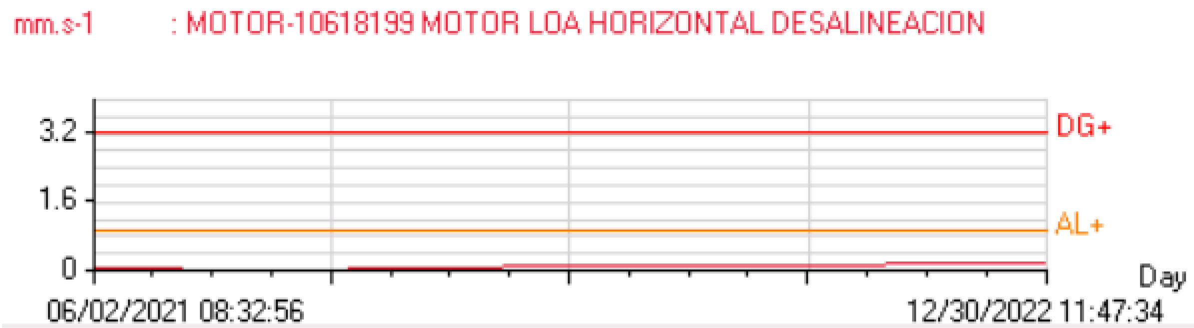

Figure IV.11. Motor bearing misalignment compared to the alarm and stop levels at G2I [38]

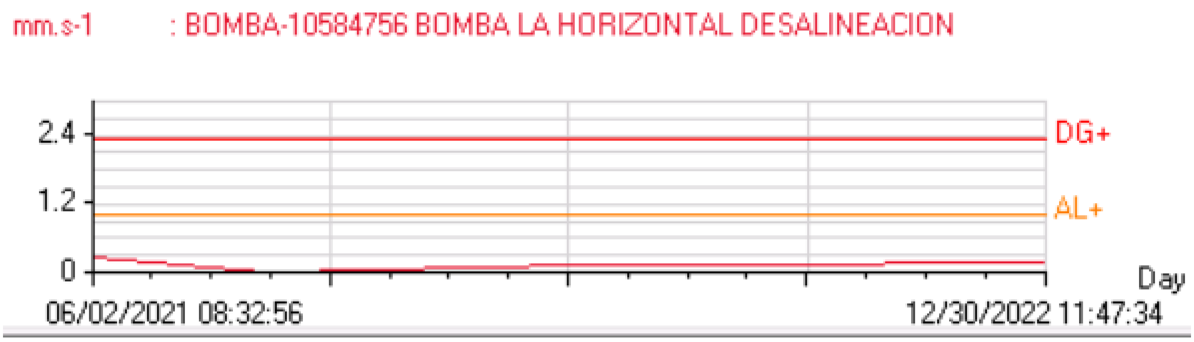

Figure IV.12. Pump bearing misalignment compared to the alarm and stop levels at G2I [38]

3. *G1 SG II*:

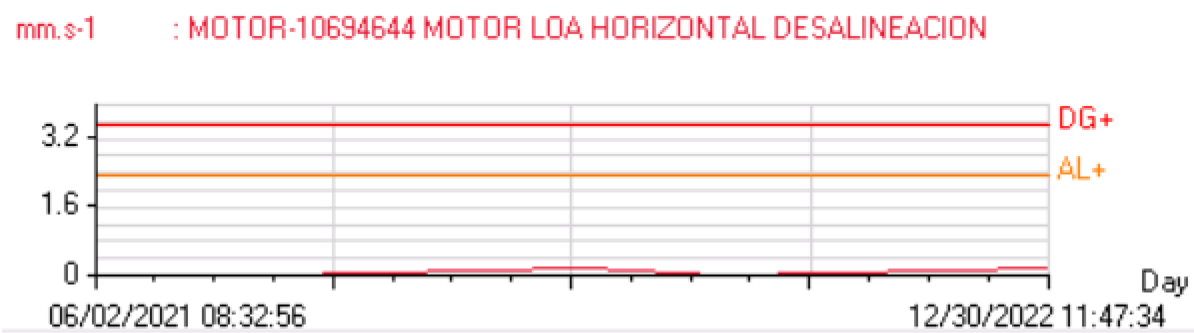

Figure IV.13. Motor bearing misalignment compared to the alarm and stop levels G1II [38]

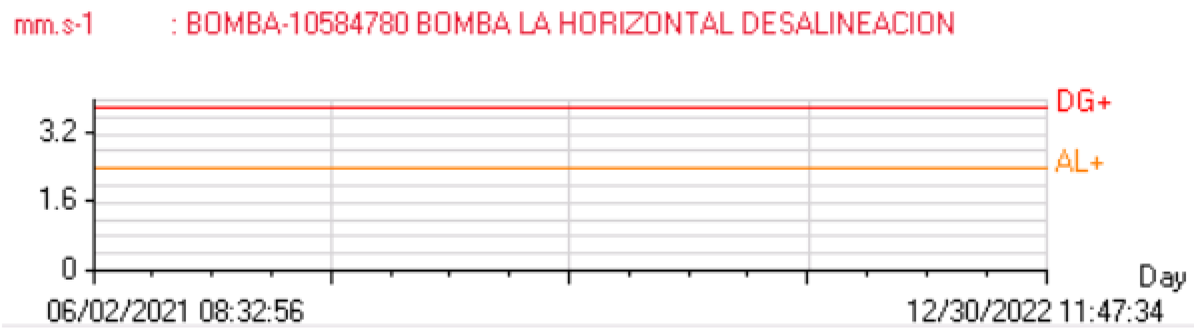

Figure IV.14. Pump bearing misalignment compared to the alarm and stop levels at G1II [38]

4. *G2 SG II*:

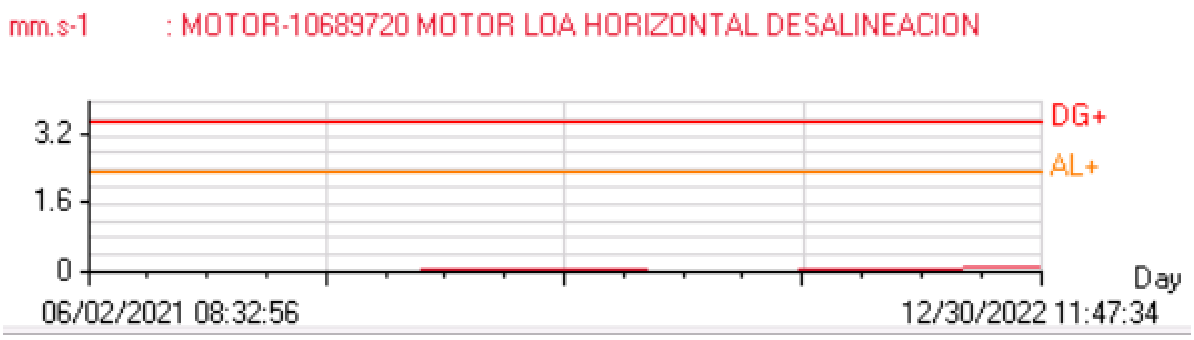

Figure IV.15. Motor bearing misalignment compared to the alarm and stop levels G2II [38]

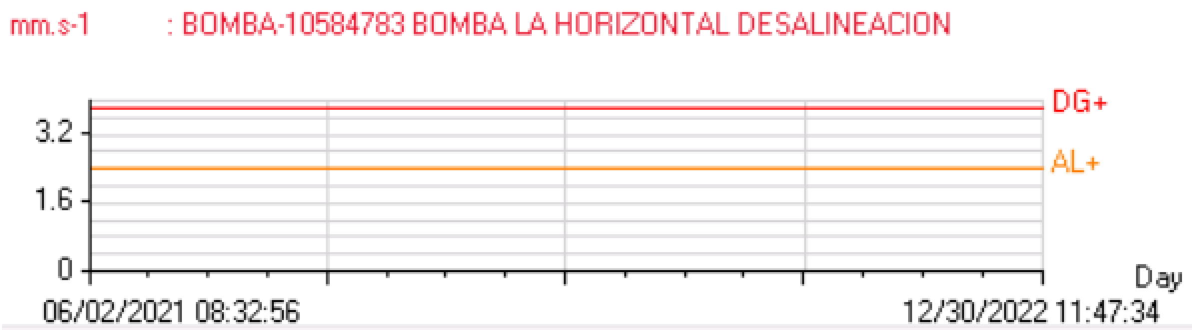

Figure IV.16. Pump bearing misalignment compared to the alarm and stop levels at G2II [38]

- ***ACELERACIÓN* or Acceleration:**

1. *G1 SG I*:

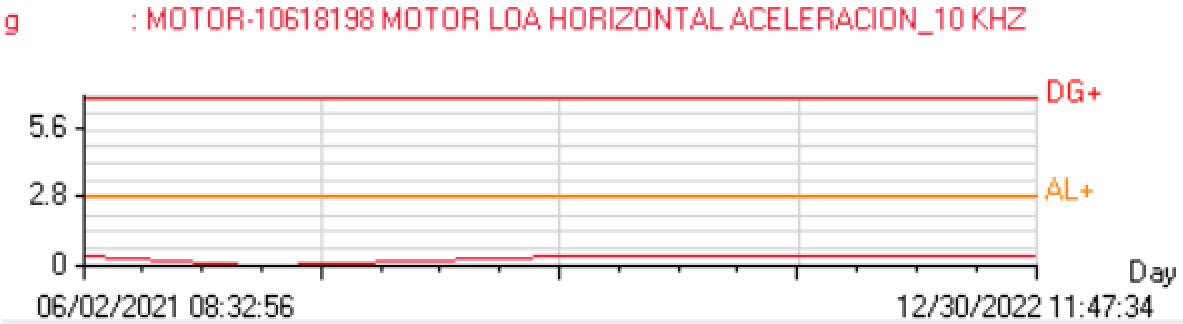

Figure IV.17. Motor bearing acceleration compared to the alarm and stop levels at G1I [38]

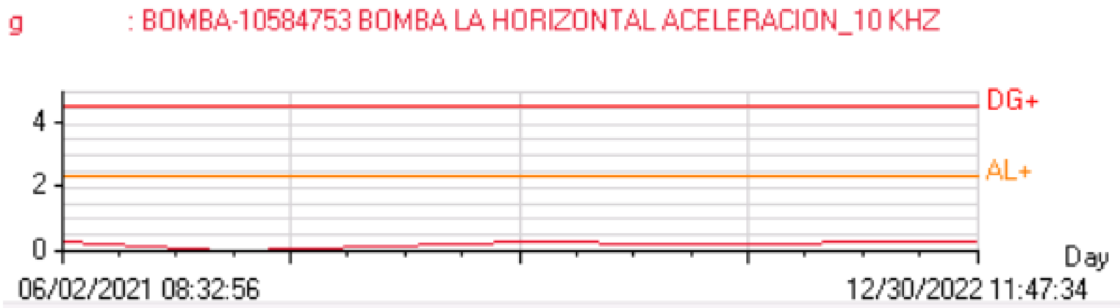

Figure IV.18. Pump bearing acceleration compared to the alarm and stop levels at G1I [38]

2. *G2 SG I*:

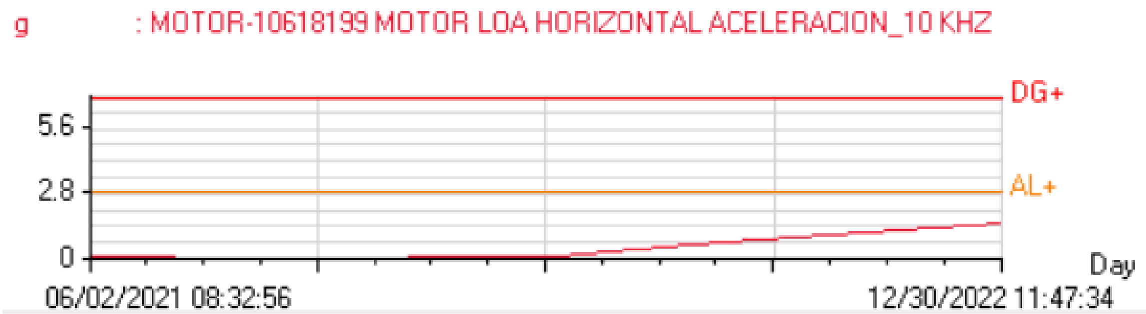

Figure IV.19. Motor bearing acceleration compared to the alarm and stop levels at G2I [38]

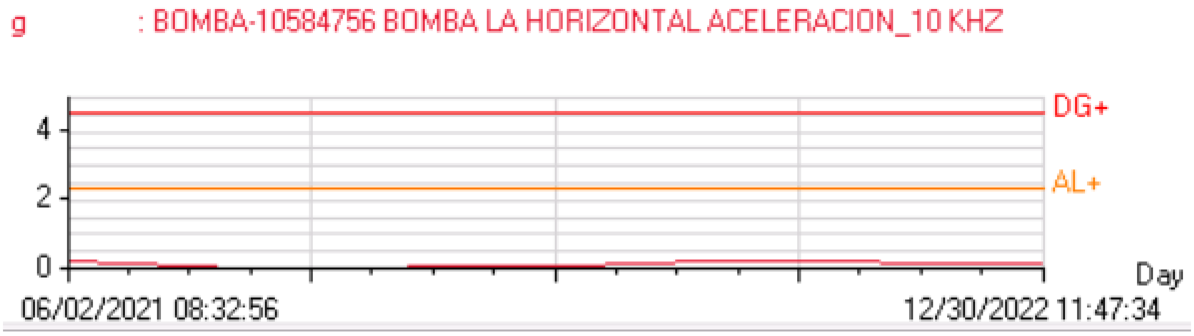

Figure IV.20. Pump bearing acceleration compared to the alarm and stop levels at G2I [38]

3. *G1 SG II*:

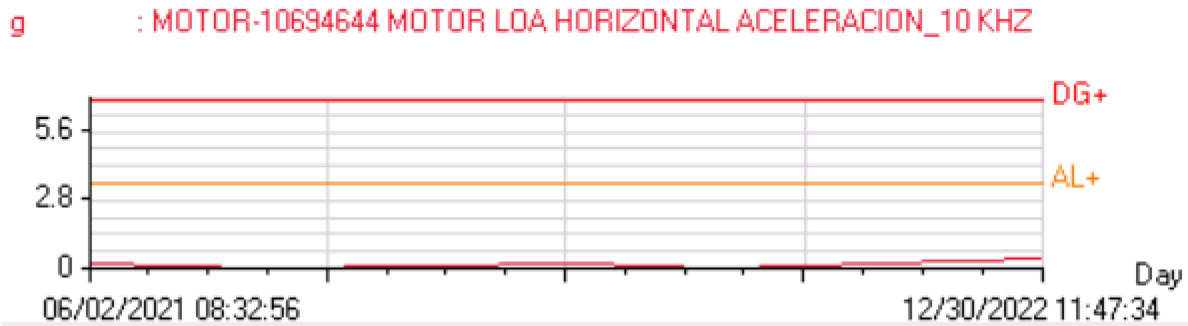

Figure IV.21. Motor bearing acceleration compared to the alarm and stop levels at G1II [38]

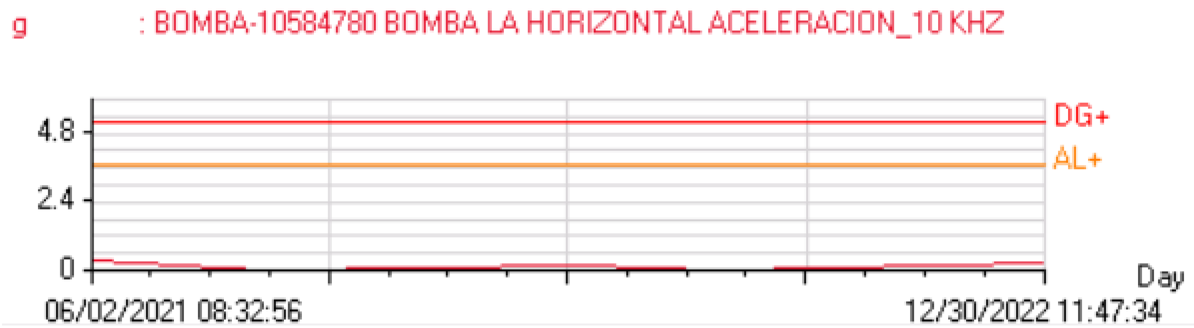

Figure IV.22. Pump bearing acceleration compared to the alarm and stop levels at G1II [38]

4. *G2 SG II*:

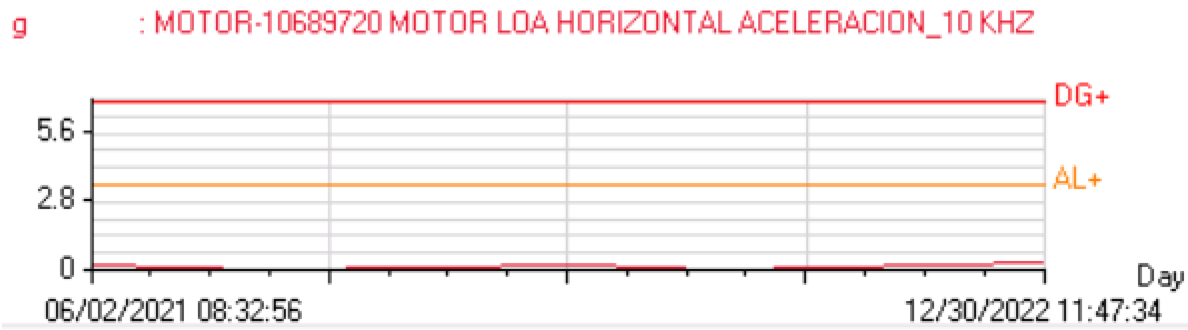

Figure IV.23. Motor bearing acceleration compared to the alarm and stop levels at G2II [38]

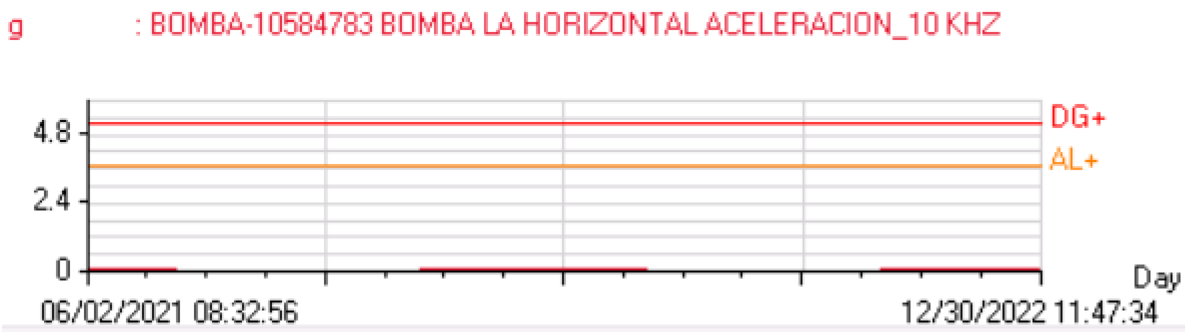

Figure IV.24. Pump bearing acceleration compared to the alarm and stop levels at G2II [38]

- ***BAJA FREC.* or Low Frequency Filter:**

1. *G1 SG I*:

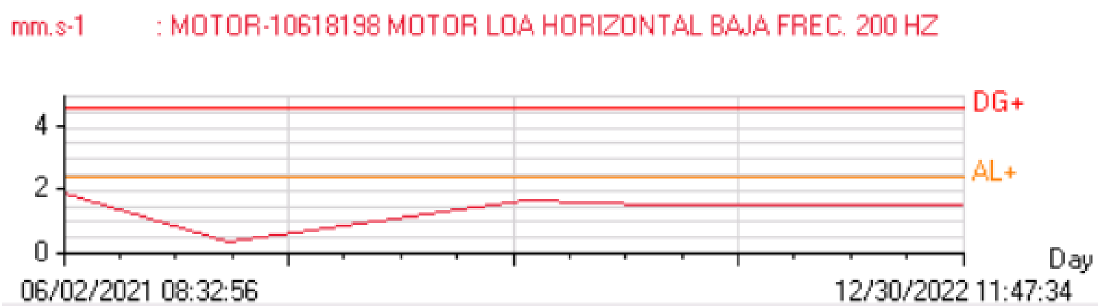

Figure IV.25. Motor bearing low range compared to the alarm and stop levels at G1I [38]

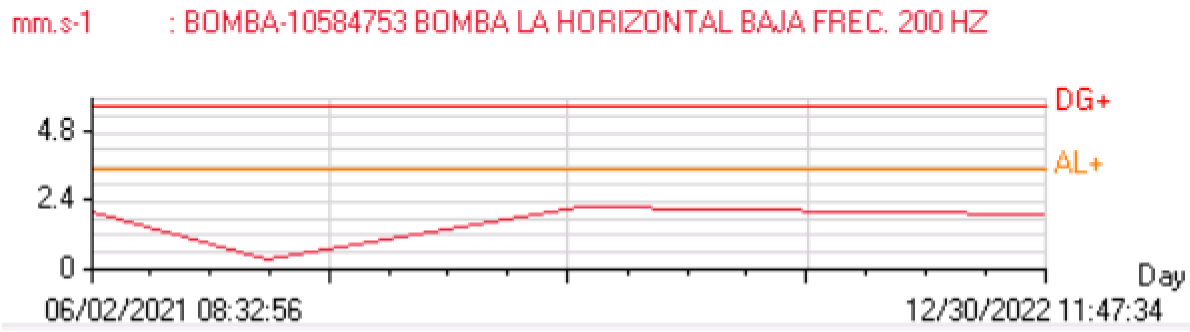

Figure IV.26. Pump bearing low range compared to the alarm and stop levels at G1I [38]

2. *G2 SG I*:

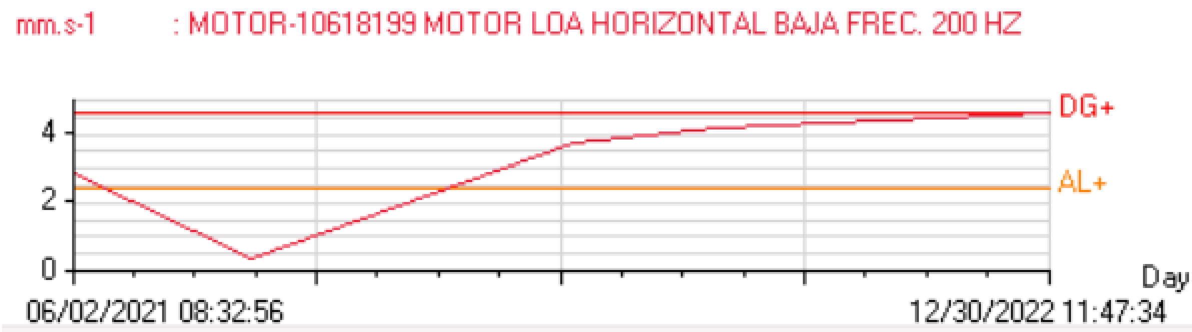

Figure IV.27. Motor bearing low range compared to the alarm and stop levels at G2I [38]

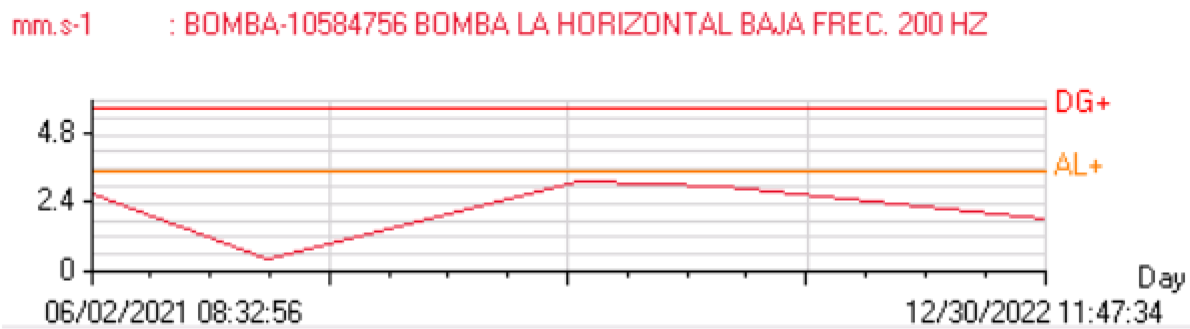

Figure IV.28. Pump bearing low range compared to the alarm and stop levels at G2I [38]

3. *G1 SG II*:

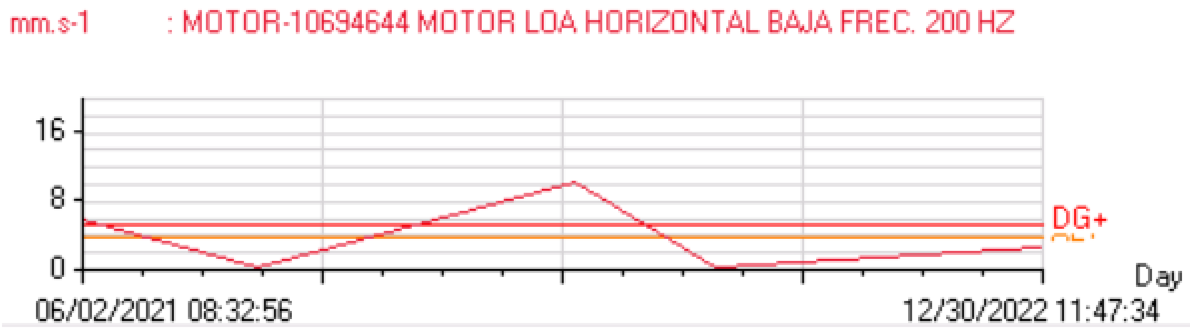

Figure IV.29. Motor bearing low range compared to the alarm and stop levels at G1II [38]

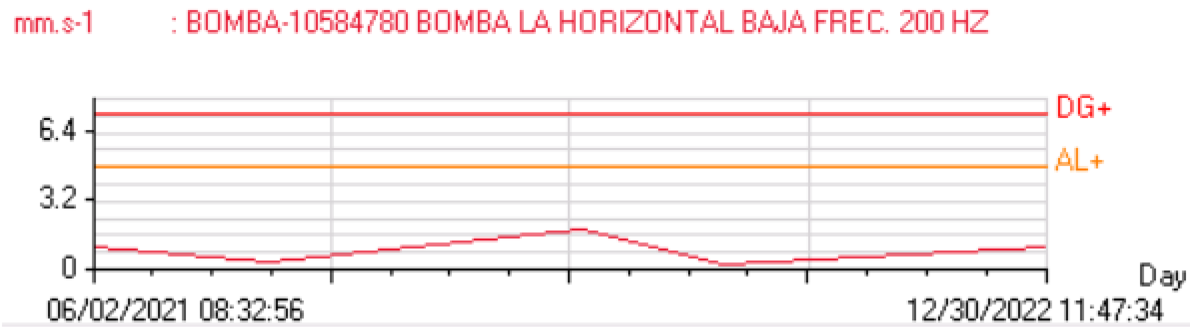

Figure IV.30. Pump bearing low range compared to the alarm and stop levels at G1II [38]

4. *G2 SG II*:

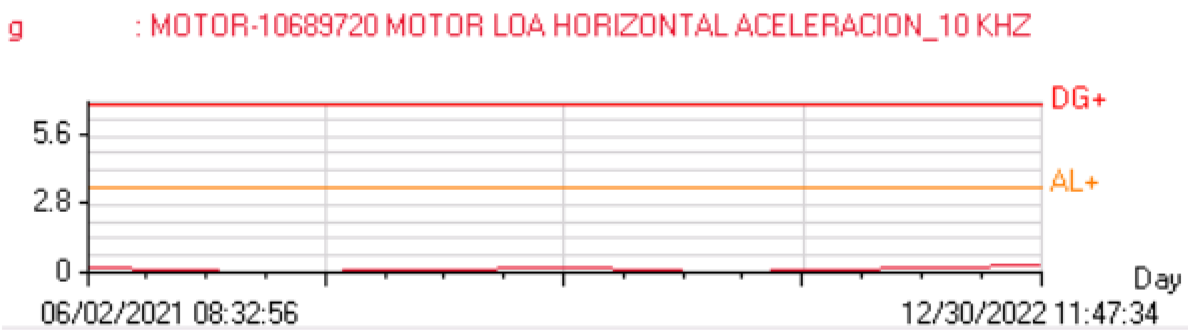

Figure IV.31. Motor bearing low range compared to the alarm and stop levels at G2II [38]

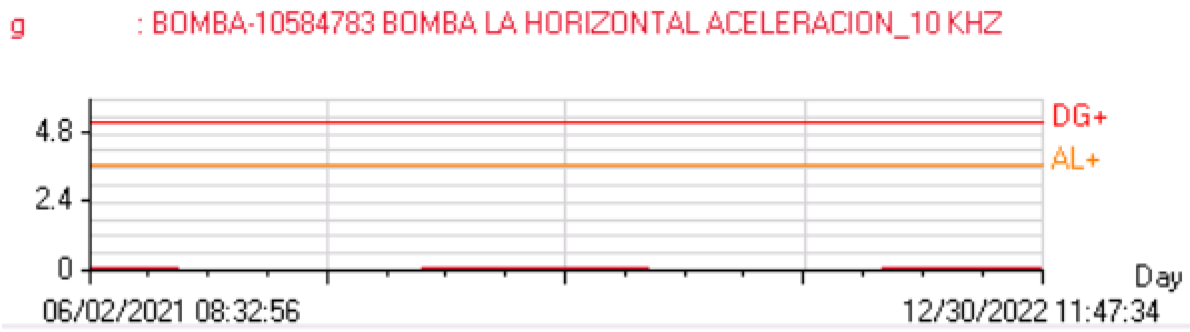

Figure IV.32. Pump bearing low range compared to the alarm and stop levels at G2II [38]

- ***MEDIA FREC* or Mid Frequency Filter:**

  1. *G1 SG I*:

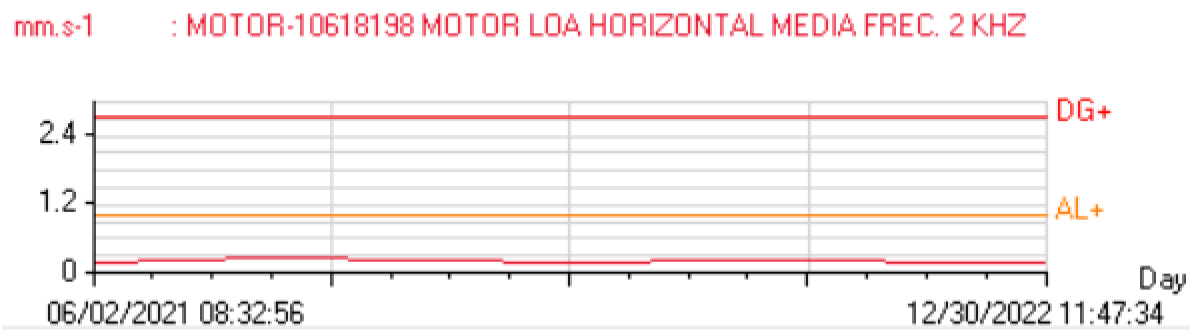

Figure IV.33. Motor bearing mid range compared to the alarm and stop levels at G1I [38]

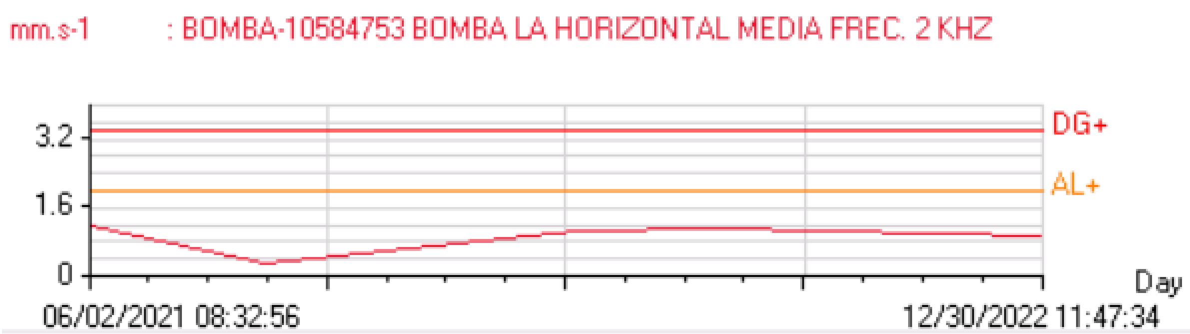

Figure IV.34. Pump bearing mid range compared to the alarm and stop levels at G1I [38]

2. *G2 SG I*:

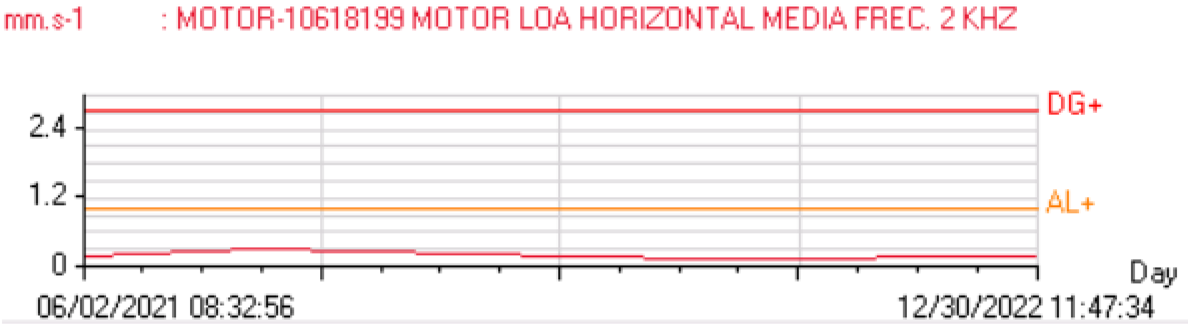

Figure IV.35. Motor bearing mid range compared to the alarm and stop levels at G2I [38]

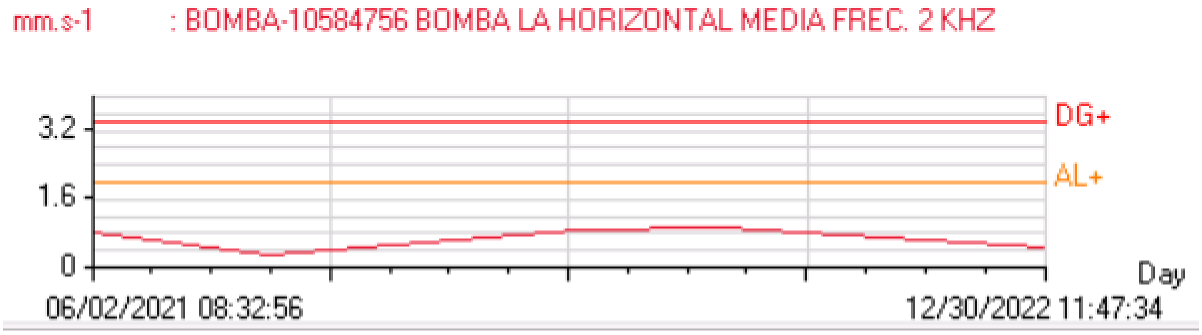

Figure IV.36. Pump bearing mid range compared to the alarm and stop levels at G2I [38]

3. *G1 SG II*:

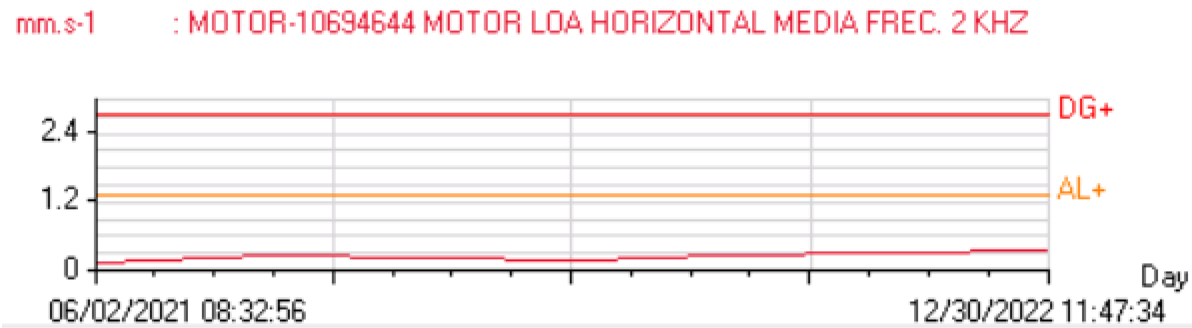

Figure IV.37. Motor bearing mid range compared to the alarm and stop levels at G1II [38]

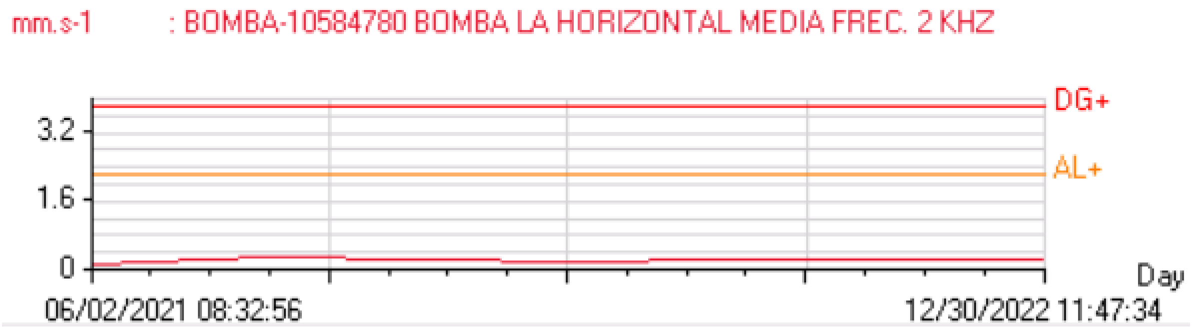

Figure IV.38. Pump bearing mid range compared to the alarm and stop levels at G1II [38]

4. *G2 SG II*:

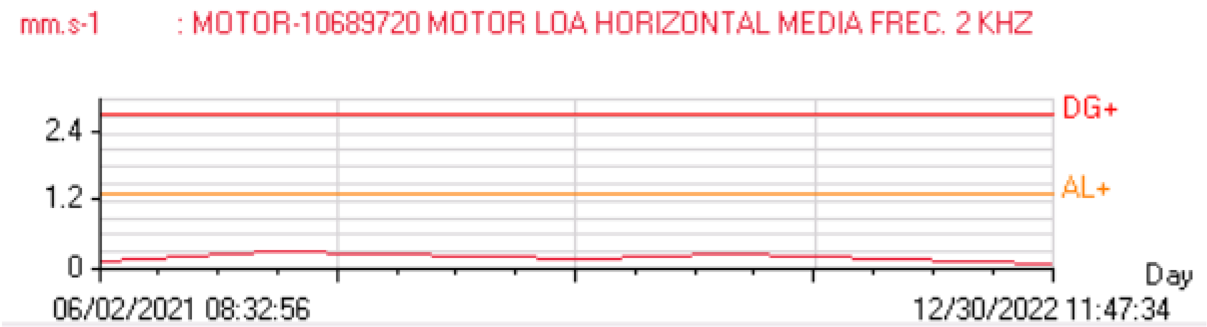

Figure IV.39. Motor bearing mid range compared to the alarm and stop levels at G2II [38]

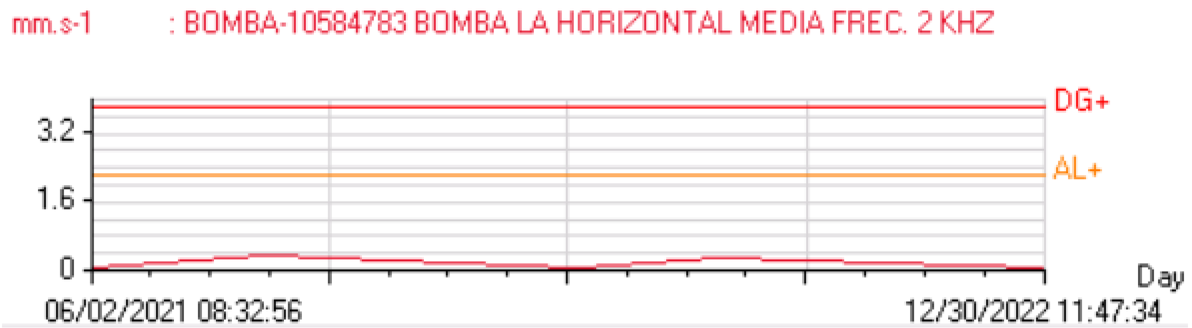

Figure IV.40. Pump bearing mid range compared to the alarm and stop levels at G2II [38]

- ***DEFECTO ROD.* or Bearing Defect:**

1. *G1 SG I*:

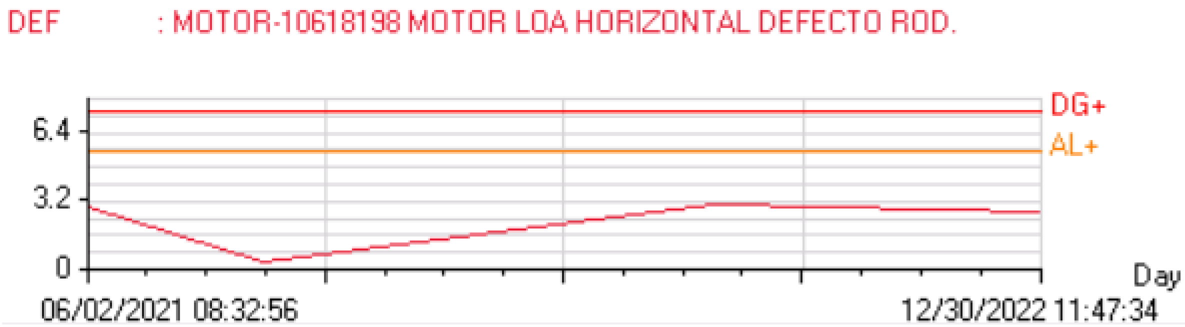

Figure IV.41. Motor bearing defect status compared to the alarm and stop levels at G1I [38]

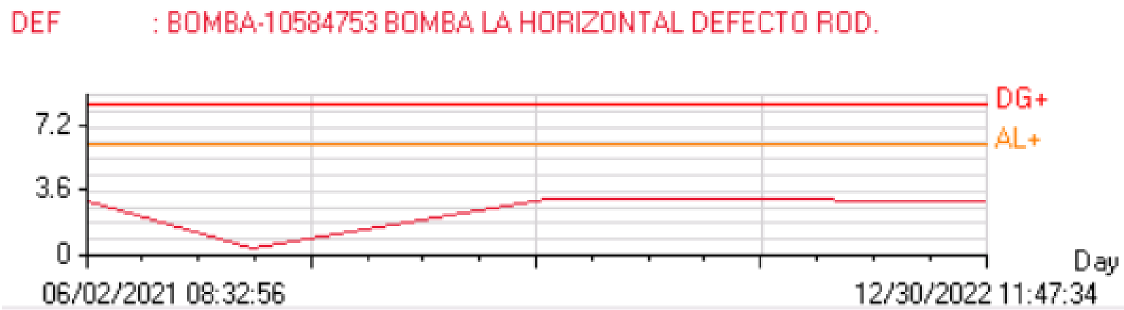

Figure IV.42. Pump bearing defect status compared to the alarm and stop levels at G1I [38]

2. *G2 SG I*:

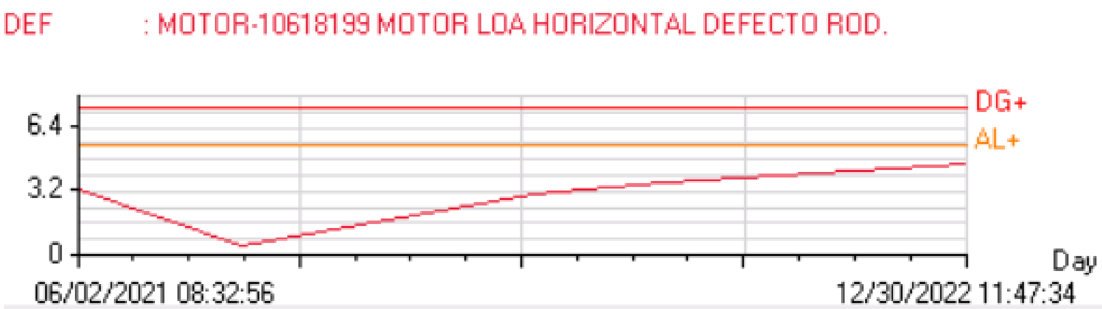

Figure IV.43. Motor bearing defect status compared to the alarm and stop levels at G2I [38]

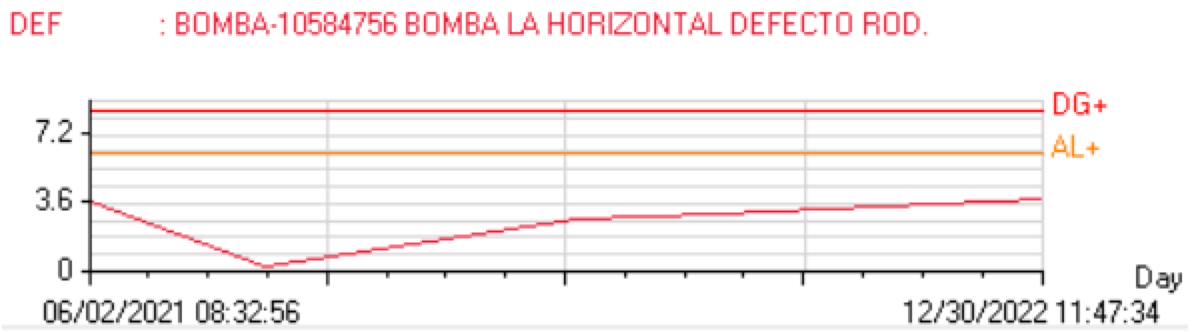

Figure IV.44. Pump bearing defect status compared to the alarm and stop levels at G2I [38]

3. *G1 SG II*:

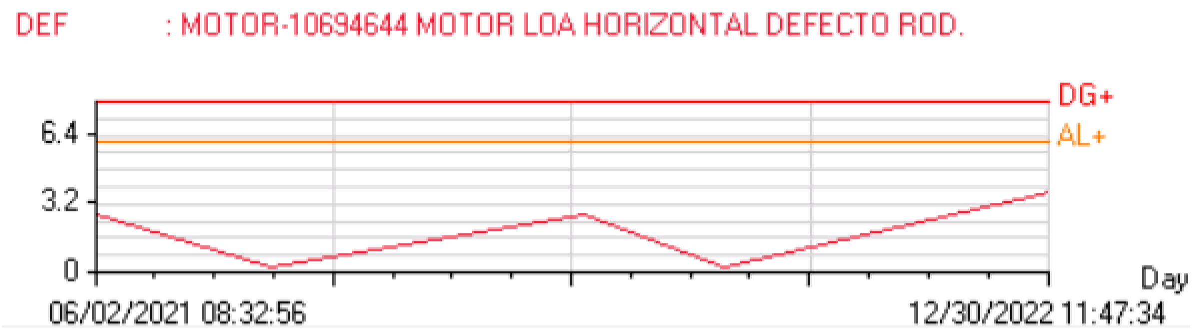

Figure IV.45. Motor bearing defect status compared to the alarm and stop levels at G1II [38]

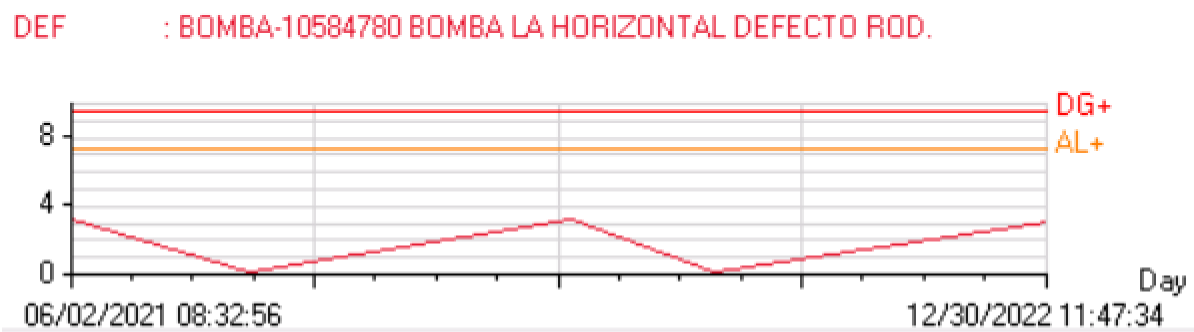

Figure IV.46. Pump bearing defect status compared to the alarm and stop levels at G1II [38]

4. *G2 SG II*:

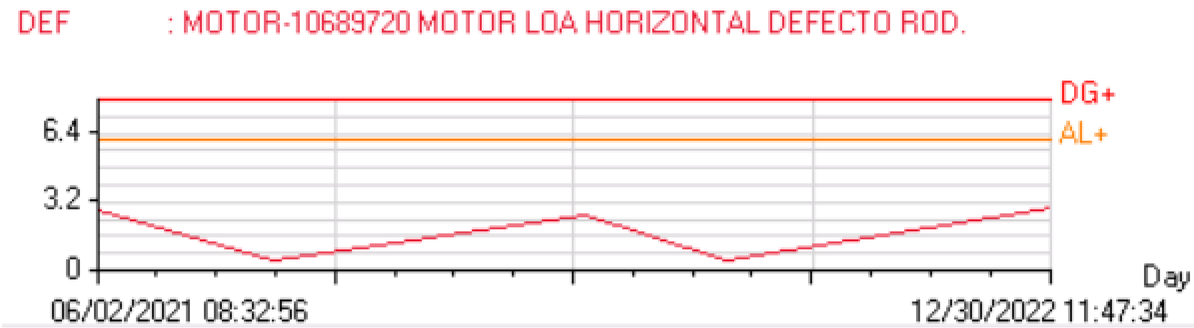

Figure IV.47. Motor bearing defect status compared to the alarm and stop levels at G2II [38]

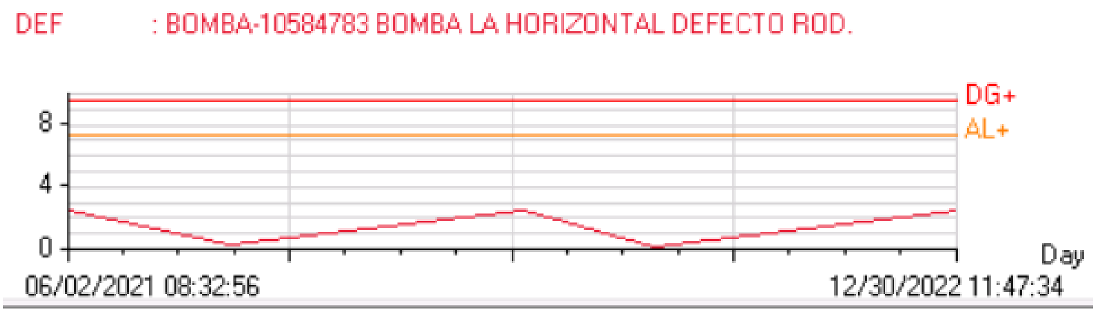

Figure IV.48. Pump bearing defect status compared to the alarm and stop levels at G2II [38]

- ***VALOR GLOBAL* or Global Value:**

1. *G1 SG I*:

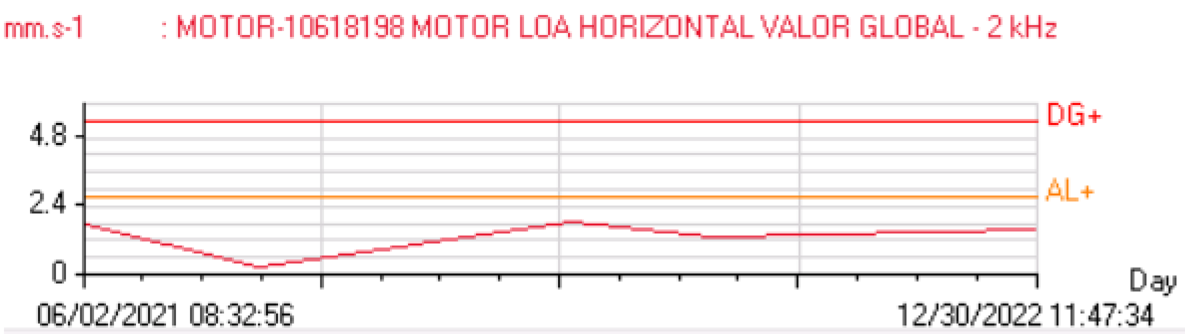

Figure IV.49. Motor bearing global status compared to the alarm and stop levels at G1I [38]

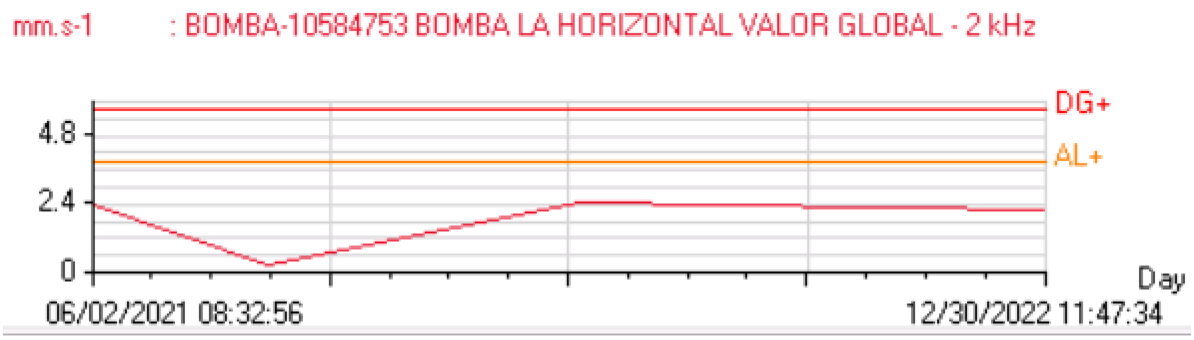

Figure IV.50. Pump bearing global status compared to the alarm and stop levels at G1I [38]

2. *G2 SG I*:

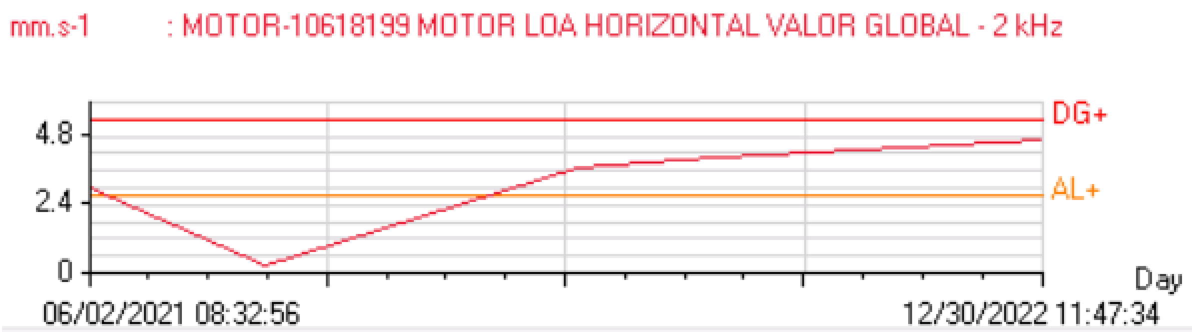

Figure IV.51. Motor bearing global status compared to the alarm and stop levels at G2I [38]

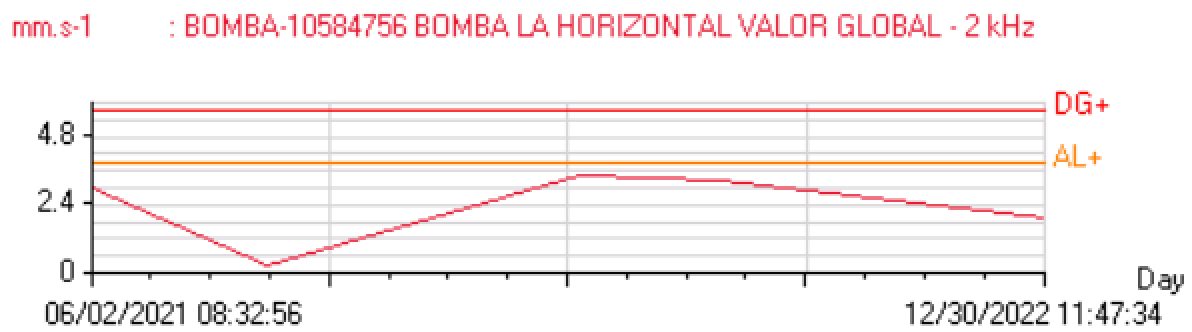

Figure IV.52. Pump bearing global status compared to the alarm and stop levels at G2I [38]

3. *G1 SG II*:

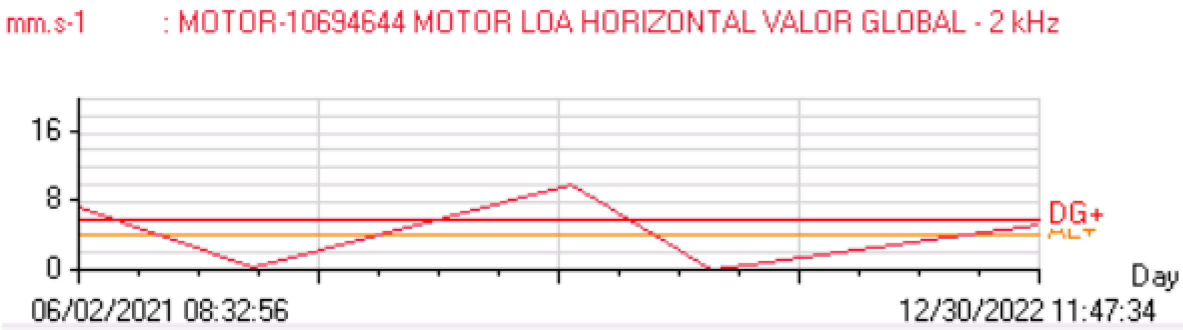

Figure IV.53. Motor bearing global status compared to the alarm and stop levels at G1II [38]

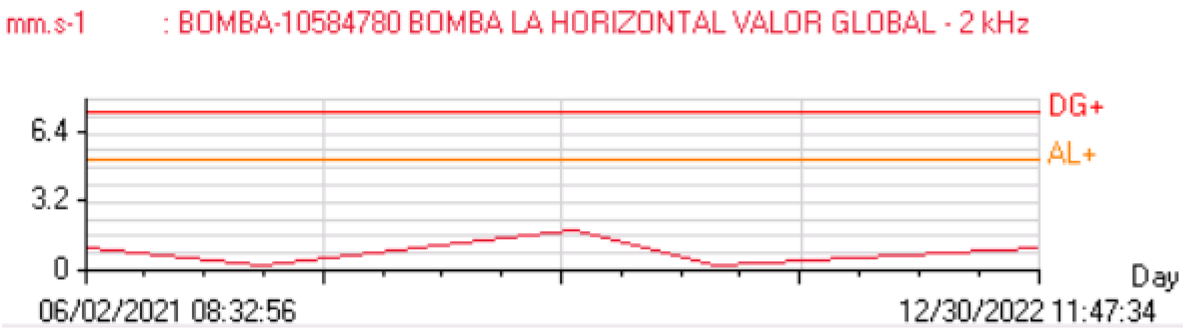

Figure IV.54. Pump bearing global status compared to the alarm and stop levels at G1II [38]

4. *G2 SG II*:

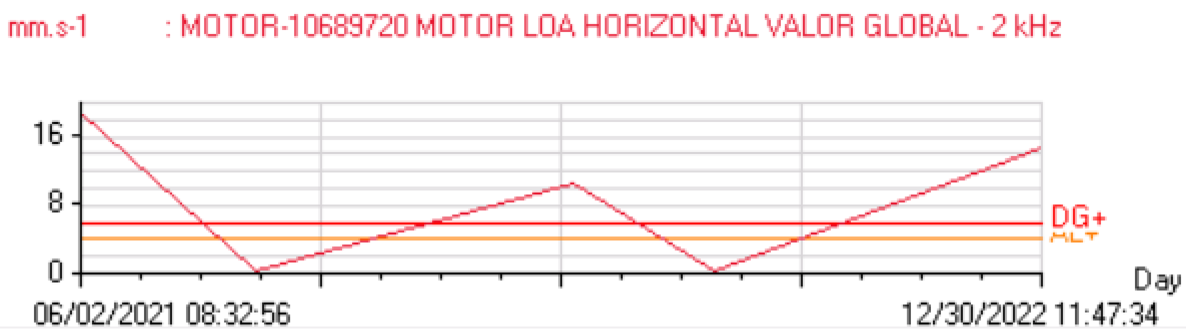

Figure IV.55. Motor bearing global status compared to the alarm and stop levels at G2II [38]

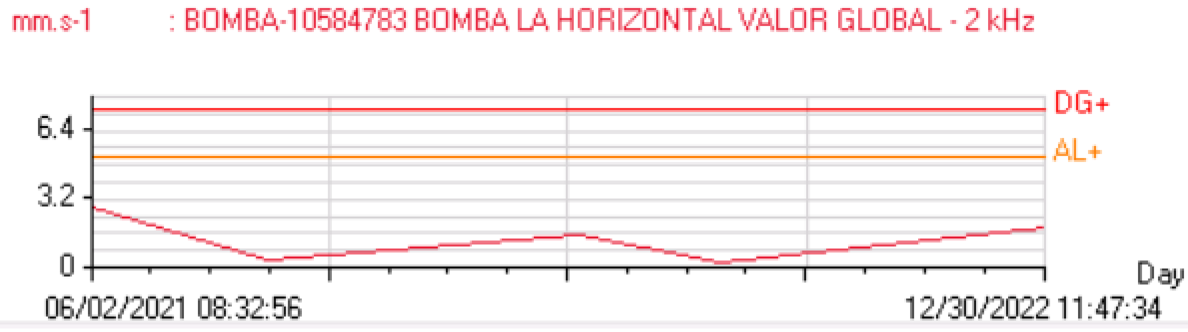

Figure IV.56. Pump bearing global status compared to the alarm and stop levels at G2II [38]

ANNEX V: *SG* MONITORING EVOLUTION

This ANNEX presents the evolution of other *SG* stations. It has been used in order to expect the future behavior of the *G3* terminal.

- *G1 SG I*:

PSS	MOTOR	MOTOR	MOTOR	MOTOR	MOTOR
VALOR GLOBAL –	1.87	1.02	1.84	0.762	1.73
DEFECTO ROD.	2.29	2.44	2.42	2.33	2.67
DESEQUILIBRIO	1.24	0.617	1.50	0.352	1.05
DESALINEACION	0.176	0.286	0.135	0.222	0.640
EXCENTRICIDAD - 1C	0.105	0.058	0.096	0.091	0.040
ACELERACION_10 KH	0.430	0.466	0.405	0.339	0.310
BAJA FREC. 200 HZ	1.73	1.03	1.74	0.758	1.73
MEDIA FREC. 2 KHZ	0.187	0.145	0.139	0.119	0.158
TEMPERATURA	20.0		27.1		
P-P Forma de onda		?		?	
Kurtosis		?		?	

Figure V.1. *G1 SG I* motor indicators after the monitoring [38]

PSS	BOMBA I	BOMBA I	BOMBA I	BOMBA I	BOMBA I
VALOR GLOBAL –	2.47	1.55	1.09	1.42	1.15
DEFECTO ROD.	3.27	2.94	2.61	2.76	2.67
DESEQUILIBRIO	1.13	0.799	0.545	0.115	0.420
DESALINEACION	0.810	0.104	0.135	0.834	0.133
ACELERACION_10 KH	0.311	0.272	0.143	0.198	0.189
BAJA FREC. 200 HZ	2.27	1.51	0.967	1.33	0.915
MEDIA FREC. 2 KHZ	1.11	0.414	0.395	0.554	0.682
P-P Forma de onda		?			?
TEMPERATURA	28.2			22.4	
Kurtosis		?			?

Figure V.2. *G1 SG I* pump indicators after the monitoring [38]

As the final results of the *G1 I* show, the monitoring ended in a great condition, but some defects were found in the process.

In December of 2011, the global condition value of the motor and pump bearings exceeded the stop level due to unbalance. The motor bearings were afflicted a second time during August of 2015 by the unbalance:

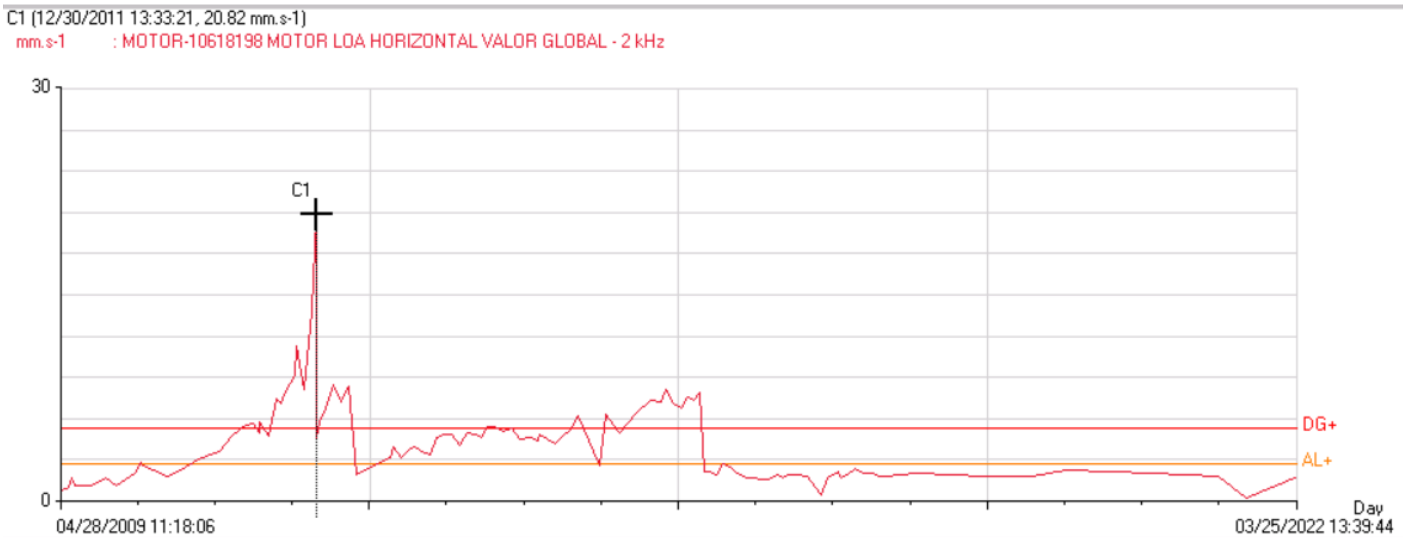

Figure V.3. *G1 SG I* motor first unbalance [38]

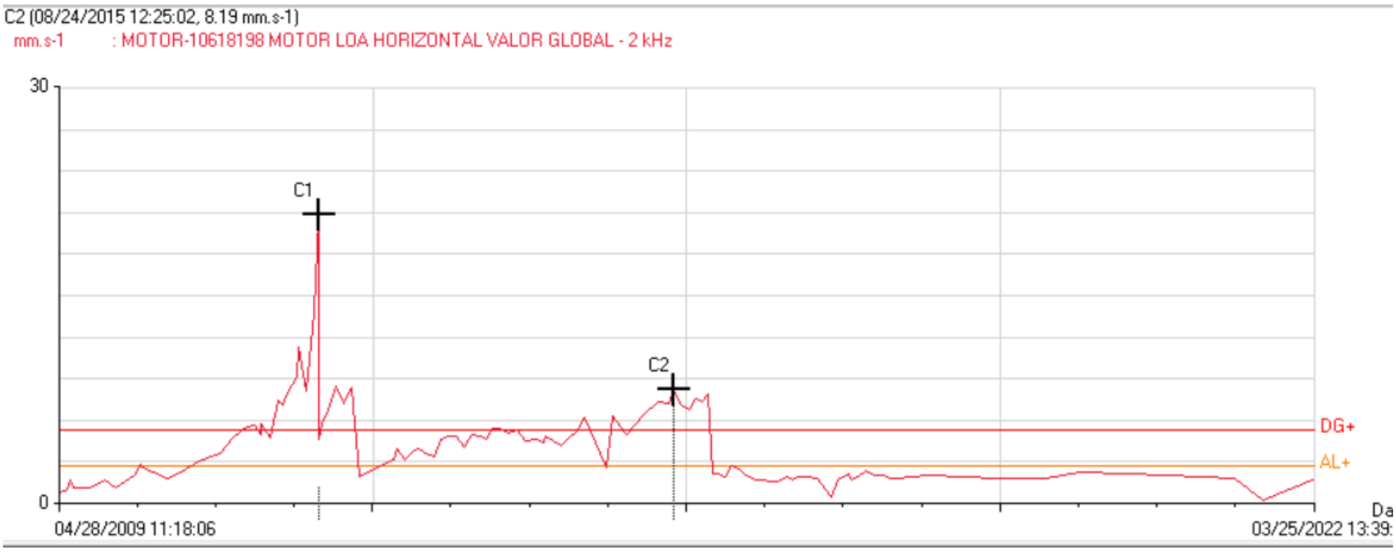

Figure V.4. *G1 SG I* motor second unbalance [38]

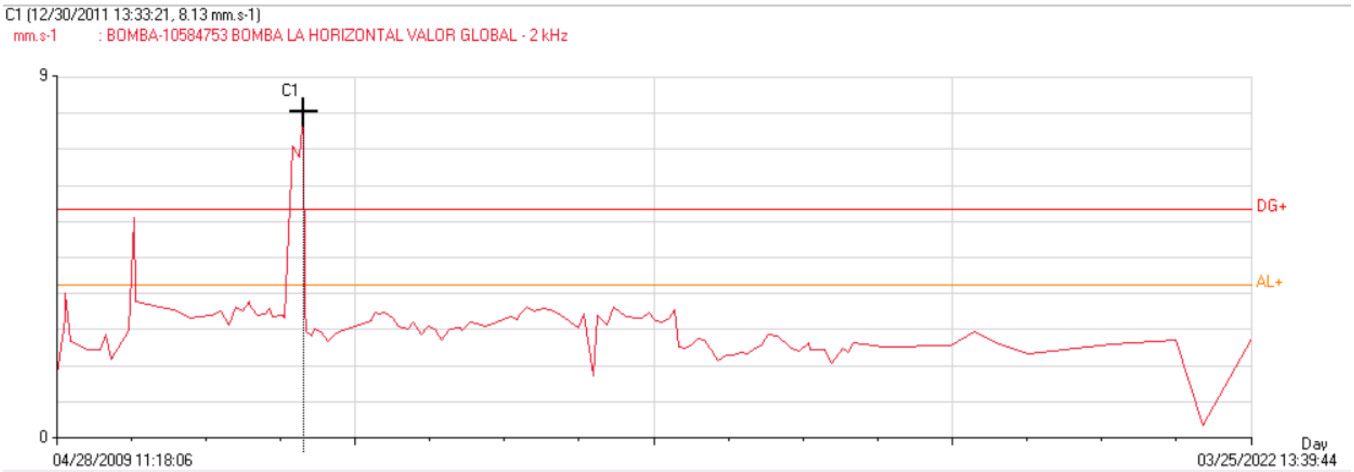

Figure V.5. *G1 SG I* pump unbalance [38]

- *G2 SG I*:

PSS	MOTOR	MOTOR	MOTOR	MOTOR	MOTOR
VALOR GLOBAL –	3.78	1.92	3.30	1.04	2.25
DEFECTO ROD.	3.11	3.91	3.85	3.20	3.69
DESEQUILIBRIO	3.13	0.930	2.69	0.358	2.00
DESALINEACION	0.129	0.222	0.047	0.216	0.089
EXCENTRICIDAD - 1C	0.801	0.043	0.458	0.033	0.193
ACELERACION_10 KH	0.165	0.427	0.839	0.271	0.525
BAJA FREC. 200 HZ	3.80	1.90	3.24	1.04	2.17
MEDIA FREC. 2 KHZ	0.218	0.136	0.131	0.104	0.123
TEMPERATURA	25.1		32.0		
P-P Forma de onda		?		?	
Kurtosis		?		?	

Figure V.6. *G2 SG I* motor indicators after the monitoring [38]

PSS	BOMBA I	BOMBA I	BOMBA I	BOMBA I	BOMBA I
VALOR GLOBAL –	3.51	1.80	1.54	2.23	1.76
DEFECTO ROD.	2.79	2.75	3.06	2.54	3.46
DESEQUILIBRIO	2.91	1.50	0.811	1.53	1.18
DESALINEACION	0.173	0.172	0.200	0.133	0.280
ACELERACION_10 KH	0.144	0.156	0.152	0.194	0.180
BAJA FREC. 200 HZ	3.25	1.70	1.50	1.97	1.65
MEDIA FREC. 2 KHZ	0.893	0.425	0.352	0.974	0.555
P-P Forma de onda		?			?
TEMPERATURA	30.9			30.9	
Kurtosis		?			?

Figure V.7. *G2 SG I* pump indicators after the monitoring [38]

As the final results of the *G2 I* show, the monitoring ended in an alarmant state.

In April of 2012, the global condition value of the motor bearings exceeded the stop level due to unbalance. On the other side, the pump bearings kept their initial condition during all the process:

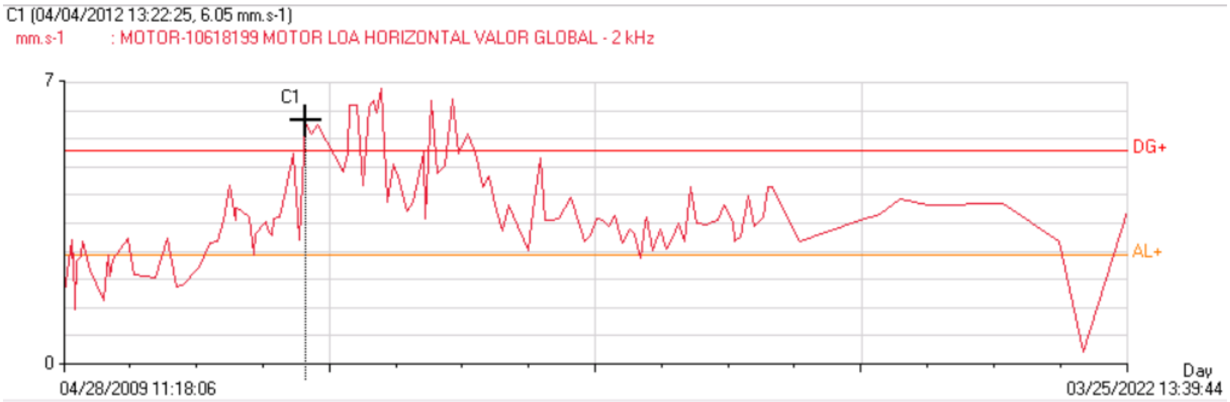

Figure V.8. *G2 SG I* motor unbalance [38]

Figure V.9. *G2 SG I* pump state [38]

- *G1 SG II*

PSS	MOTOR	MOTOR	MOTOR	MOTOR	MOTOR
VALOR GLOBAL –	10.3	4.05	3.84	3.45	0.974
DEFECTO ROD.	2.82	2.87	2.45	2.38	2.51
DESEQUILIBRIO	10.0	3.78	3.59	3.19	0.804
DESALINEACION	0.205	0.090	0.090	0.158	0.032
EXCENTRICIDAD - 1C	0.427	0.207	0.201	0.074	0.118
ACELERACION_10 KH	0.297	0.277	0.159	0.209	0.167
BAJA FREC. 200 HZ	10.3	3.90	3.73	3.27	0.938
MEDIA FREC. 2 KHZ	0.215	0.222	0.161	0.246	0.194
TEMPERATURA	17.7		22.8		
P-P Forma de onda		?		?	
Kurtosis		?		?	

Figure V.10. *G1 SG II* motor indicators after the monitoring [38]

PSS	BOMBA I	BOMBA I	BOMBA I
VALOR GLOBAL –	1.91	1.42	0.535
DEFECTO ROD.	3.27	2.81	3.81
DESEQUILIBRIO	1.80	1.31	0.444
DESALINEACION	0.029	0.071	0.026
ACELERACION_10 KH	0.260	0.205	0.426
BAJA FREC. 200 HZ	1.92	1.37	0.499
MEDIA FREC. 2 KHZ	0.222	0.201	0.213
P-P Forma de onda		?	
TEMPERATURA	23.8		
Kurtosis		?	

Figure V.11. *G1 SG II* pump indicators after the monitoring [38]

Unexpectedly, the pump bearings were in a great condition at the end of the monitoring while the motor bearings were found close to the internal damage of the machine. The *G1 II* had a completely different behavior than the other terminals presented due to the unbalance appearing in the bearings only afflicted the motor after ten years of operation. As seen, the defect could not be repaired, implying a sudden breakdown of the machine between 2019 and 2022:

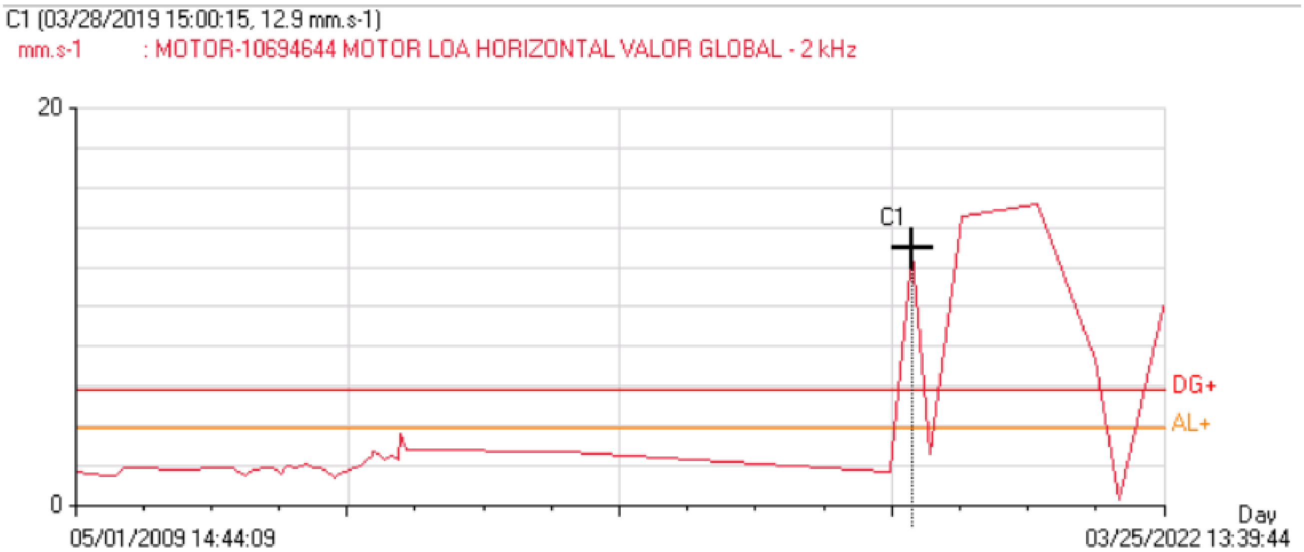

Figure V.12. *G1 SG II* motor unbalance [38]

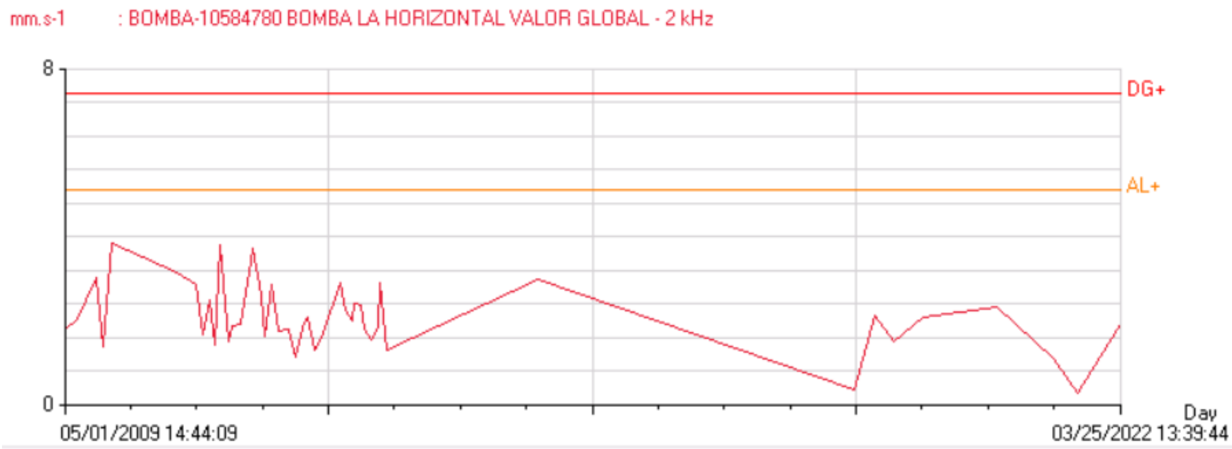

Figure V.13. *G1 SG II* pump great condition [38]

- *G2 SG II*:

PSS	MOTOR	MOTOR	MOTOR	MOTOR	MOTOR
VALOR GLOBAL –	10.6	3.22	5.22	1.11	1.71
DEFECTO ROD.	2.66	2.64	2.49	5.31	2.32
DESEQUILIBRIO	10.1	3.04	4.93	1.21	1.58
DESALINEACION	0.072	0.077	0.056	0.064	0.065
EXCENTRICIDAD - 1C	0.070	0.047	0.041	0.017	0.061
ACELERACION_10 KH	0.217	0.187	0.133	0.132	0.099
BAJA FREC. 200 HZ	10.4	3.13	5.07	3.63	1.64
MEDIA FREC. 2 KHZ	0.195	0.272	0.103	0.142	0.123
TEMPERATURA	20.4		32.7		
P-P Forma de onda		?		?	
Kurtosis		?		?	

Figure V.14. *G2 SG II* motor indicators after the monitoring [38]

PSS	BOMBA I	BOMBA I	BOMBA I
VALOR GLOBAL –	1.59	0.873	0.653
DEFECTO ROD.	2.55	2.38	2.41
DESEQUILIBRIO	1.45	0.811	0.594
DESALINEACION	0.018	0.034	0.038
ACELERACION_10 KH	0.136	0.090	0.132
BAJA FREC. 200 HZ	1.51	0.854	0.633
MEDIA FREC. 2 KHZ	0.105	0.098	0.098
P-P Forma de onda		?	
TEMPERATURA	23.9		
Kurtosis		?	

Figure V.15. *G2 SG II* pump indicators after the monitoring [38]

Similarly to the *G1 SG II* station, the *G2* is lately afflicted by the unbalance in the motor bearings during 2019, after ten years of monitoring:

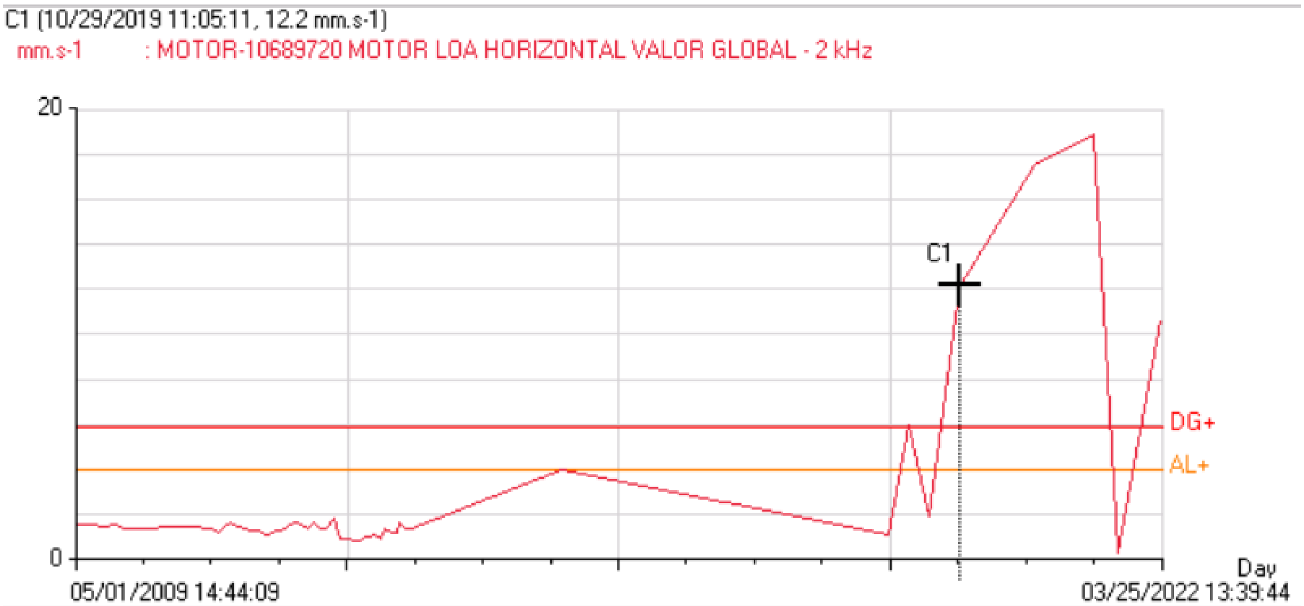

Figure V.16. *G2 SG II* motor unbalance [38]

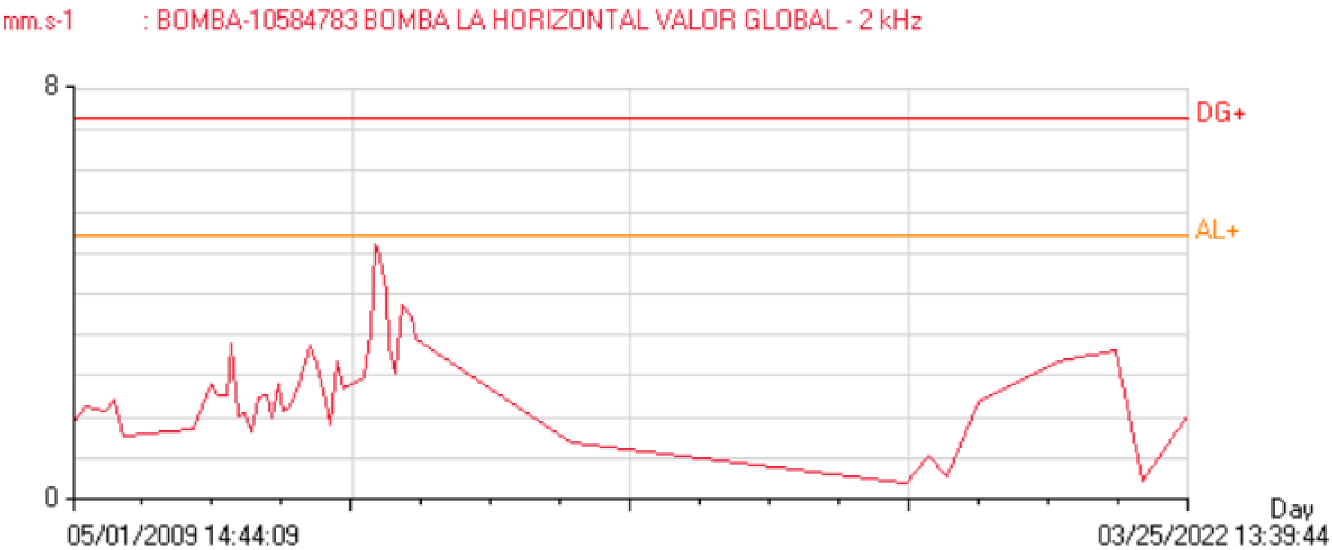

Figure V.17. *G2 SG II* pump great condition [38]

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