People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific Research
University of Yahia Fares – Medea
Faculty of technology
Department of mechanical engineering

Thesis

Presented to obtain a diploma of MASTER

in

Mechanical Construction

Title

Monitoring a centrifugal compressor through vibration analysis

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June 2024

الملخص

الهدف من هذا المشروع، الخاص بنهاية دراسات الماستر في الإنشاء الميكانيكي، هو متابعة سلوك ضواغط الطرد المركزي الخاصة بإنتاج الغاز الطبيعي باستعمال تحليل الاهتزازات.

في هذا المشروع قمنا بالتقاط الإشارة الحقيقية دون أي معالجة من الحساس المتواجد داخل الضاغط والتي تم تحويلها من تيار كهربائي الى المجال الرقمي عن طريق وسائل وتقنيات مناسبة، تم حفظ هذه الإشارة على شكل جداول ثم تم استغلالها لتحليل الاهتزازات باستعمال برنامج MATLAB وبعد المعالجة تم الحصول على بيانات بدلالة الزمن وأرقام وأطياف تم استعمالها لاتخاذ قرارات حول صيانة الضاغط مع الاحتفاظ بالتجربة لتجنبها مستقبليا.

كلمات مفتاحية: تحليل الإشارة، ضاغط الطرد المركزي، تحليل الاهتزازات، حساس الحركة، التردد

Abstract

The objective of this project, for the end of the master's studies in mechanical engineering, is the monitoring of the behavior of centrifugal compressors of natural gas production using vibration analysis. In this project, we acquired the raw signal from the sensors mounted at the journal bearing, which was converted from an electric current to the digital domain using appropriate technologies. This signal was recorded in tabular form, then used to analyze vibration using MATLAB software, and then obtained figures, numbers and spectra that have been used to make decisions about compressor maintenance while retaining this experience to operate in the future.

Keywords: signal processing, centrifugal compressor, vibration analysis, proximity probe, frequency

Résumé

L'objectif de ce projet, de fin d'études de master en construction mécanique, est la Surveillance du comportement des compresseurs centrifuges de production de gaz naturel en utilisant l'analyse vibratoire. Dans ce projet, nous avons acquis le signal réel sans aucun traitement venant des capteurs montés au niveau de palier porteurs du compresseur, qui a été converti à partir d'un courant électrique vers le domaine numérique par des moyens et des technologies adéquat, Ce signal a été enregistré sous forme de tableaux, puis utilisé pour analyser les vibrations à l'aide logiciel MATLAB ,et a ensuite obtenu des figures, des nombres et des spectres qui ont été utilisés pour prendre des décisions sur la maintenance du compresseur tout en conservant cet expérience pour exploiter à l'avenir.

Mot clés : traitement de signal, compresseur centrifuge, analyse vibratoire, capteur de proximité, fréquence

ACKNOWLEDGMENTS

First of all, I would like to express my gratitude to **Allah**, the most merciful, for blessing us with good health and peace of mind to stay strong in completing this dissertation.

I am deeply thankful to my supervisor, **Dr. Nasereddine AMOURA**, for his invaluable help, precious advice, and guidance. I truly appreciate all his comments and advice to improve my work.

I would also like to express my heartfelt thanks to my company supervisor **Mr. Lamine ZAOUI** for their support and assistance throughout this journey.

Deepest appreciation is extended to the jury members **Pr. Abdellah ABDELLAH-ELHADJ** and **Pr. Mouloud BOUMAHDI** who devoted their times and energies to examine this work.

Furthermore, I am immensely grateful to **my mother, my father, my wife** and all **my family**, for their unwavering support, encouragement, and understanding. Their love and encouragement have been a source of strength and motivation for me throughout this endeavor.

I must also extend a special thank you to **Dr. Abdennour ELMOHRI** ,**Dr. Abderahman BENAISSA and Mr. Sif-elhak BOUZAREDILMI**, who played a pivotal role during my Master's registration.

Additionally, I express my gratitude to **the workers** of the **Vibration Analysis Service** and the **Centrifugal Compressor Maintenance service** for their significant contributions to this project. Moreover, I am thankful to **all those who have assisted me**, even with just a word of encouragement.

Last but not least, I extend my gratitude to all **the teachers** and **students** who participated in this work and played a fundamental role in its completion.

And to **whoever taught me a word**, thank you.

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GENERAL INTRODUCTION

GENERAL INTRODUCTION

In contemporary time, in Algeria, energy production in the oil & gas sector has become a major challenge, especially after the decrease in natural pressure levels in the gas and petroleum reservoir, which is why the situation has been remedied by the establishment of boosting Station to increase the crude gas pressure, so that we can process and filter it before it is converted to the market and to the consumer.

These stations have many rotating equipment among them (gas turbine, pumps, compressors and others) wich play a strategic role in the production chain for example, at the boosting station, the compressor is the beating heart of the station, and so that the production process is done in an uninterrupted manner.

The company 'SONATRACH' have invested in huge means of maintaining these machines, including protective control of compressors and predictive maintenance techniques such as oil analysis, efficiency analysis and monitoring through vibration analysis .

This latter is a technique widely used, and its effectiveness is currently taking a very important place in the implementation of a predictive maintenance policy.

The wide variety of vibration problems encountered on mechanical equipment leads to the development of specific signatures using different signal processing techniques. The most widely used processing method is spectral analysis, the objective of which is to determine the evolution over time of the different lines present in the measurement signal spectrum, that is why we chose to focus on «monitoring a centrifugal compressor through vibration analysis», the monitoring methods applied and the equipment used at SONATRACH Hassi R'mel to detect anomalies and the study of the vibration phenomena of the centrifugal compresors make it possible to detect virtually all the defects likely to appear in the rotating machines (unbalance, looseness, misalignment, etc.

The thesis is organized into four chapters:

The first chapter provides an overview of the Hassi Rmel region and the application of predictive maintenance within the company. **In the second chapter**, we defined centrifugal compressors, their types, components and undesirable phenomena encountered during their operation, such as surge, axial thrust and radial vibrations, which will be the subject of our **third chapter**. Indeed, the latter are among the most recurrent and the most present on the rotating machines. We will present

the practical techniques of vibration signal analysis and processing. Finally, in the **fourth chapter**, to close this study on vibration analysis and signal processing, we will treat a real case using the MATLAB software to make an adequate decision.

1st Chapter The implementation of predictive maintenance at Hassi Rmel

1.1 Introduction

Hassi Rmel is located on the Saharan platform, near the North Eastern edge of the Sahara between the great Erg in the south and flexure Aplasique in the North, about 600 km to South of Algiers, part of the Wilaya of LAGHOUAT and distant 120 Km from GHARDAÏA, has an altitude of about 720 m.

Hassi Rmel has a very large gas field composed primarily of natural gas and a fraction of oil. These two products, found initially, require treatment units that have undergone continuous development during this decade.

The gas field is 80 km from north to south and 50 km from east to west, comprising approximately 300 gas producing wells, 52 gas injector wells, 20 oil wells, 05 modules (dry gas production plants, condensate and L.P.G) ,03 boosting stations, 02 compressor stations, 05 oil processing centers ,01 station for recovery associated gas, 01 center for storage and transfer and another small station for production also.

The regional management of Hassi Rmel has for essential mission, the exploitation and the production of gas and oil (crude) from wells in the region, gas collection and dispatching to ARZEW, SKIKDA, ITALY and SPAIN via TUNISIA and BENI SAF as well as maintenance of operating and production equipment.

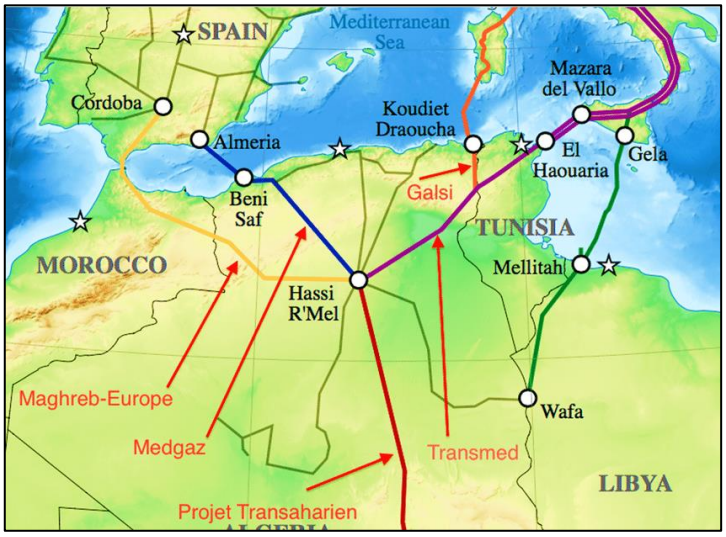


Figure 1-1 Geographical position of Hassi R'mel and paths of petroleum energy pipelines in Algeria

Crude gas consists mainly of:

- Dry Gas or sales Gas (C1, C2).
- Liquefied propane gas "LPG" (C3, C4).
- Condensate (C5 and above)

1.2 Hassi Rmel field activities

The Hassi Rmel field consists of three operating areas (northern, center and southern) [2]

- Northern Zone: consists of Module 3, northern boosting station 'NBS' and North Compressor Station 'NCS'
- Central Zone: consists of Module 0, Module 1 and Module 4, storage and transfer center of fluids 'STCF', the national center of dispatching gas 'NCDG', the Station of recovery associated gas 'SRAG', center boosting station 'CBS'.
- Southern zone: consists of module 2, southern boosting station 'SBS', southern compressor station 'SCS'

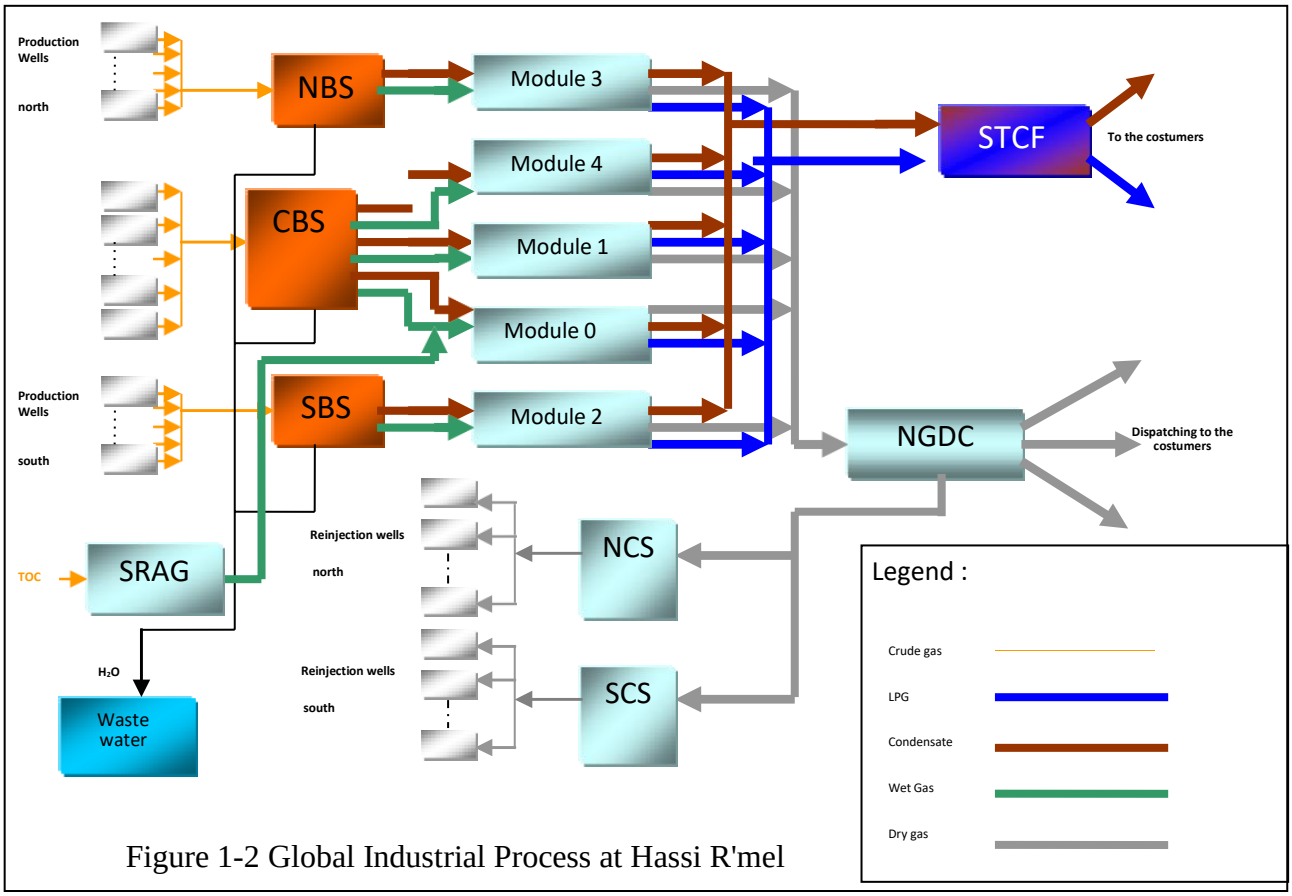


Figure 1-2 Global Industrial Process at Hassi R'mel

1.2.1.1 Module

Module, it is the diminutive of "Module Processing Plant" it designates a natural gas processing plant on an industrial scale.

Five modules are located on the Hassi Rmel field, four have a unit capacity of 60 million m3/ day, the zero module has a capacity of 30 million m3/ day. He is the oldest.

Arriving at the treatment units from the producing wells, the raw natural gas is a mixture of hydrocarbon (liquid and gaseous) and water, with some impurities.

The essential role of the treatment unit is to separate the liquid part (condensate, LPG, water) from the gaseous part (wet gas) in the first step, and to process them separately in the second step, in order to produce condensate, LPG and dry gas to certain specifications.

These specifications must be complied with in order to facilitate the transport, storage and marketing of these products.

1.2.1.2 Compressor stations

The purpose of compressor stations is to re-inject dry gas into the reservoir to :

- Maintain reservoir pressure
- Recover liquid hydrocarbons (condensate, LPG).
- Flexibility of operation.

Their locations in the north and south are defined in such a way as to have maximum recovery. The re-injection capacity of each unit is 90 million standard m3/day.

1.2.1.3 Boosting station

Before the creation of this unit, modules 0, 1, and 4 were supplied by independent wells with a reservoir pressure exceeding 100 kg/cm2. After excessive use of the wells, the pressure decreased until it reached the minimum constraint, which became a problem for production. Therefore, after studies, two solutions were suggested:

- The first was to reduce production.
- The second was to create a pressure amplification station.

- Production plays a significant role in finances, so opting for the first solution was not an option.

Therefore, the creation of the BOOSTING unit is a priority to maintain gas pressure and production volume.

The feed flow rate for the modules is 150 million m3/day:

- MPP 0: 30 million m3/day.
- MPP 1: 60 million m3/day.
- MPP 4: 60 million m3/day.

1.2.1.4 Storage and shipment of liquid hydrocarbons

The condensate and LPG produced in all gas processing modules are transported to the Storage and Transfer Centre (STCF) located in the central area of Hassi Rmel.

They pass through a separator where any solid and liquid particles (water) are recovered, counted and then shipped to Arzew.

The CSTF includes three (03) tanks with capacity of 3500 m3 and four (04) tanks with capacity 45,000 m3 each for condensate storage; twelve (12) spheres of 7000 m3 for LPG storage.

1.2.1.5 National Gas Distribution Centre (NGDC)

Its role is to collect all the quantities of gas produced at Hassi Rmel and other southern region, these quantities are then distributed to consumption centers such as LNG centers, Sonalgaz, and abroad: Italy via Tunisia and Spain via Beni-Saf.

Before being shipped to each structure, the gas collected is filtered and accounted for. Excess gas will be transported to the North and South compressor stations.

The vapors formed in the spheres, under the effect of the ambient temperature, are compressed by the turbochargers, condensed then put back for storage to avoid boille off and gas flaring

1.3 Annual Production of the Hassi Rmel field

The final development of the field resulted in the following production capacities:

- 100 billion m3 of gas per year.
- 12 million tons of condensate per year.
- 3.5 million tons of LPG per year.

To ensure these values in annual production, the Regional Directorate of HASSI RMEL recruited nearly 2,000 workers in various disciplines to ensure the durability of production.

In this thesis, we will talk about the beating heart of the company's modules, we will talk about centrifugal compressors.

There are currently around 100 centrifugal compressors in the Production Directorate when they represent an important role in the gas's production cycle so we call strategic machines.

That's why huge physical and human means to maintain and explore these compressors have been harnessed.

1.4 Hassi Rmel Regional Management

Its main mission is the development and exploitation of hydrocarbons.

To do this and to respond to its load plan properly, it has adopted the sub-directorates and divisions presented in the organizational chart below:

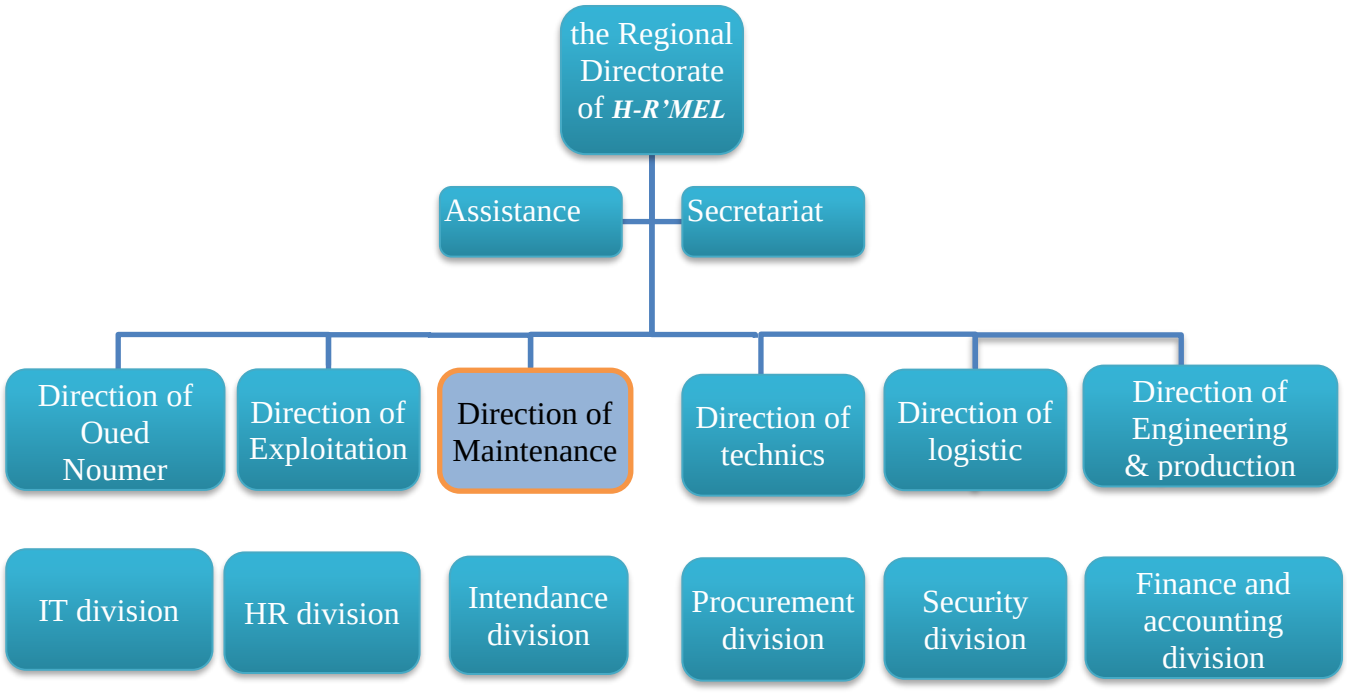


Figure 1-3 Organization chart of the Hassi Rmel regional management

1.4.1.1 Role of the direction of maintenance

Its role is:

• Planning, development, organization and implementation of maintenance reserves related to the current and future needs of the region in various activities: mechanical, electrical and instrumentation.

• Maintain equipment in good working order at a lower cost.

• Implementation of maintenance policies.

• Implementation and development of the computerized maintenance management system CMMS software.

The objectives of the maintenance department are:

- Rational and optimal equipment operation
- Reducing equipment maintenance costs
- Compliance with equipment operation regulations
- Reducing spare parts inventory.

According to the criticality of the machine in the production line , in HASSI RMEL,

we develop its own maintenance program, among them,

- ✓ We can wait until the dysfunction phase.
- ✓ There is what is applied from a strict systematic maintenance program.
- ✓ Other machines have a predictive maintenance program.

The last one generally applies in cases where the shutdown of the machine results in significant economic losses for the company so, to gain more in terms of machine life and availability in the production chain, we use predictive maintenance techniques.

as seen in Figure, predictive maintenance helps to establish a maintenance requirement only when a breakdown of the system occurs. This approach results in optimum maintenance policies and helps industries to sustain the overall health of their assets with minimal downtime

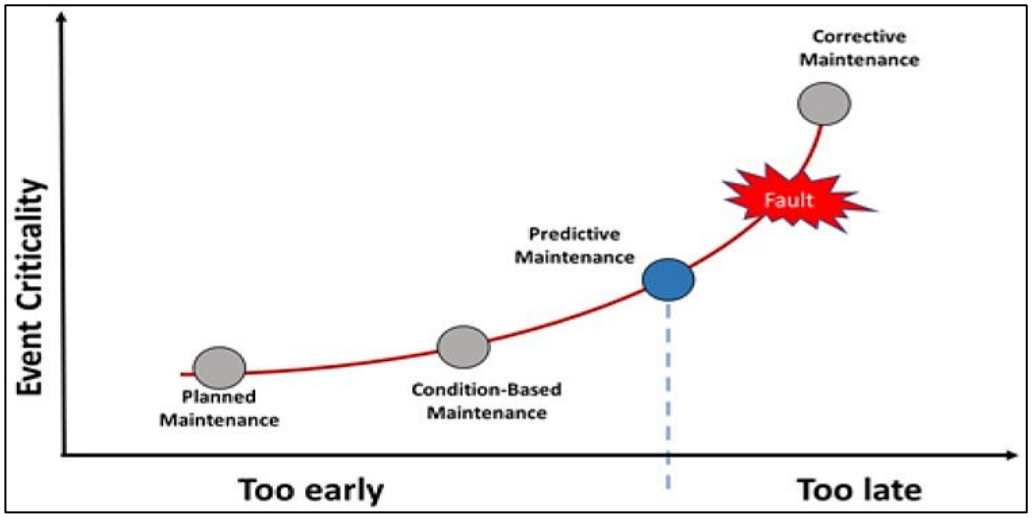


Figure 1-4 The difference between types of maintenance depending on the lifetime of the equipment.[1]

In this project, we will focus on predictive maintenance, and more specifically on vibration analysis. Because when we said predictive maintenance doesn't just mean vibration analysis.

1.5 What does it mean predictive maintenance?

1.5.1.1 Predictive maintenance definition (NF EN 13306)[3]

Condition-based maintenance carried out following a forecast derived from repeated analysis or known characteristics and evaluation of the significant parameters of the degradation of the item.

Example: for gas turbine, changes in vibration values during operation.

1.5.1.2 The essential tools of predictive maintenance[4]

A variety of technologies can be used as a part of comprehensive predictive maintenance program. Since mechanical systems or machines account for the majority of plant equipment, vibration monitoring is generally the key component of most predictive maintenance programs. However, vibration monitoring cannot provide all the information required to perform a successful predictive maintenance.

Therefore, other predictive maintenance programs have to be included.

In the diagram below, I will describe the different technologies and the essential tools of predictive maintenance.[4]

- Vibration analysis
- Lubrication oil analysis
- Analysis of operating parameter
- Thermography
- Ultrasonic monitoring
- Corrosion monitoring
- Performance monitoring

The application of these techniques can be done directly on the machines like “thermography, vibration analysis, performance, ultrasonic &corrosion monitoring”, while others require samples to be taken to the laboratory. There are those who are at the Hassi Rmel laboratories (oil analysis), while others are sent to the research and development center in Boumerdes (particle analysis).

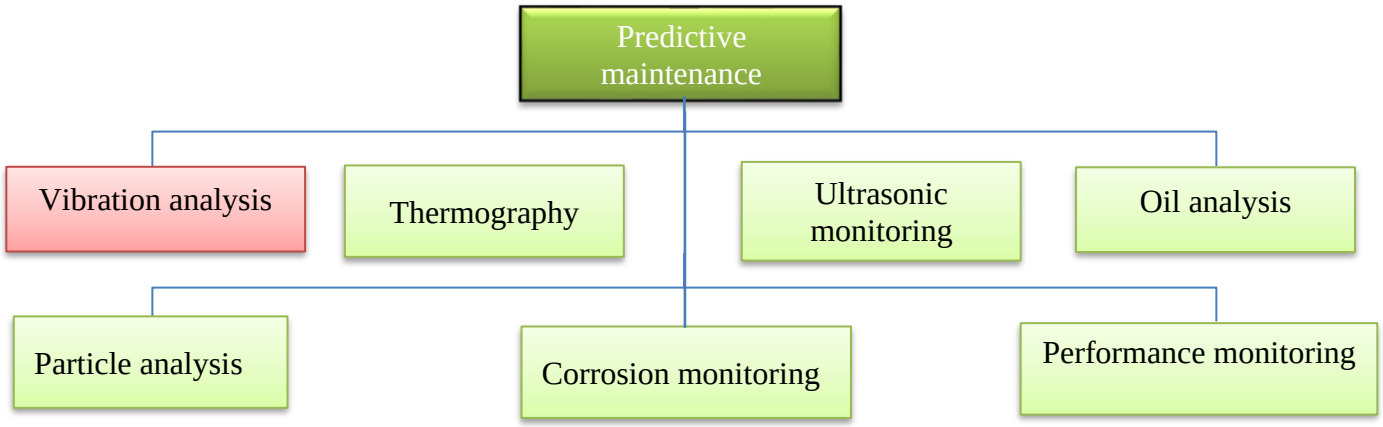


Figure 1-5 The essential tools of predictive maintenance

1.5.1.3 Vibration analysis

Vibration frequency measurement provides information about entire machine operation and condition monitoring for machine fault vibration patterns created by:

- Wear on rotating elements - bearings, shafts, gears, linkages
- Broken/missing parts - gearboxes, electric motors, compressors, pumps, conveyor drives
- Lubrication deficiency

- Impeller/fan blade material build-up
- Improper parts assembly

We will discuss this technique in more details in the third chapter.



Figure 1-6 Vibration analysis

1.5.1.4 Thermography

Thermography Figure 1-7 [5] is a predictive maintenance technique that can be used to monitor the condition of plant machinery, structures and systems. It uses instrumentation designed to monitor the emission of infrared energy, i.e., temperature, to determine their operating condition. By detecting 12 thermal anomalies, i.e., areas that are hotter or colder than they should be, an experienced surveyor can locate and define incipient problems within the plant. Infrared thermography employs computerized thermal measurement and imaging equipment to detect abnormal heating due to faulty conditions. An infrared survey can detect a problem before it manifests itself into a costly failure. Readings are taken as a part of the predictive maintenance routine and tracked over time. Failure shows up as a change in temperature. Infrared thermography helps to identify the following problems:

- Unbalanced or overloaded circuits
- Faulty electrical contacts or connections
- Improper grounding
- Bearing and coupling wear Examples of what can be scanned:
- Electrical switch gear, breakers, bus connections, and contacts.
- Transformer connections.

- Motor and generator connections, windings, feeders and exciters.



Figure 1-7 Thermography

1.5.1.5 Ultrasonic monitoring

Ultrasonic monitoring Figure 1-8 is used to detect high frequency signatures since the normal monitoring range for vibration analysis is (1Hz to 20,000Hz), but the ultrasonic technique monitors the frequency range between 20,000Hz and 100kHz. Leak (turbulent flow of liquids and gases through a restricted orifice) is mainly detected by the ultrasonic monitoring since it produces high frequency signatures that can be easily identified. In addition, ultrasonic monitoring can be used to detect early faults in elements of rotating bearings[6].

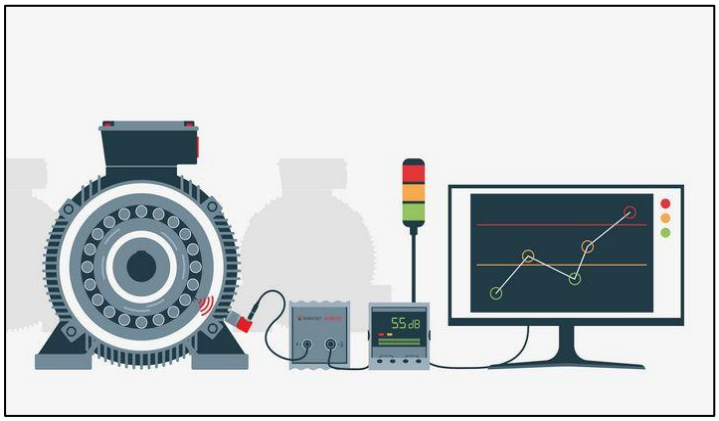


Figure 1-8 Ultrasonic monitoring

1.5.1.6 Oil analysis

One of the main predictive maintenance techniques is oil analysis. The maintenance team can find a lot of information with oil analysis and effective outcomes can be achieved.

This technique utilizes oil tests to decide hardware wear. It estimates the particularities of oil tests, like number and size, to decide machine crumbling.

Other than molecule counts, oil analysis tests can uncover the thickness, presence of water or wear metals, and the corrosive number or base number.

These molecular counts help in discovering potential problems and enable the team to overcome potential issues so that unplanned downtime can be avoided.



Figure 1-9 Oil analysis

1.5.1.7 Corrosion monitoring

Ultrasonic thickness measurements are conducted on pipelines, offshore structures and process equipment to keep track of the occurrence of corrosive wear.



Figure 1-10 Corrosion monitoring

1.5.1.8 Performance monitoring

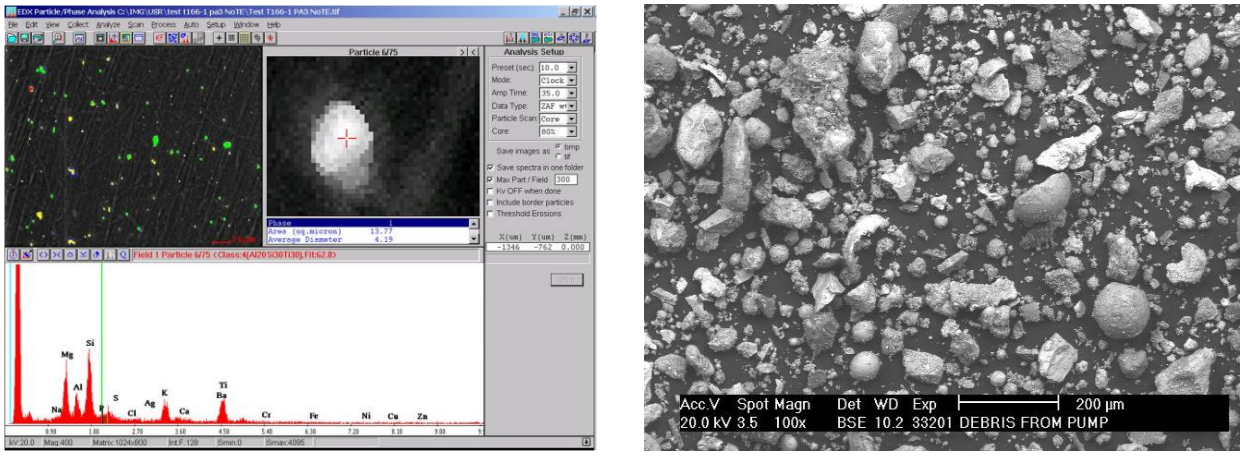
This is a very effective technique to determine the operational problems in equipment. The efficiency of machines provides a good insight on their internal conditions.

This technique is helpful in understanding performance while it is working so that the maintenance team can check if an asset is working well or need some calibration adjustments.

If adjustments need to be made then a checklist is created with a predictive maintenance solution, and this adjustment is done when asset maintenance is performed.

1.5.1.9 Particle analysis

Worn machinery components, whether in reciprocating machinery, gearboxes or hydraulic systems, release debris. Collection and analysis of this debris provides vital information on the deterioration of these components. [7]



(a) (b)

Figure 1-11 (a) Shows a Screenshot from the running Particle Analysis software; the overall image of registered particles (top left window), with the particle being analyzed shown as a thumbnail image (top right window) and the X-ray spectrum being acquired (lower window))

(b) Shows particles from pump under microscope (100X)

1.5.1.10 Steps for implementing predictive maintenance

For the four techniques mentioned above, here are the steps to follow. [4]

1.5.1.11 Detection

Detection involves measuring and trending levels for each machine included in the program on a regularly scheduled basis. The objective is to reveal significant increases in the machine level to warn of developing problem.

1.5.1.12 Analysis or Fault Diagnosis

Analysis helps to pinpoint specific machinery problems by revealing their unique characteristics.

1.5.1.13 Decision

Decision action is taken after specific problem has been detected and identified by planning and scheduling all activities to ensure that machine downtime is kept to the absolute minimum.

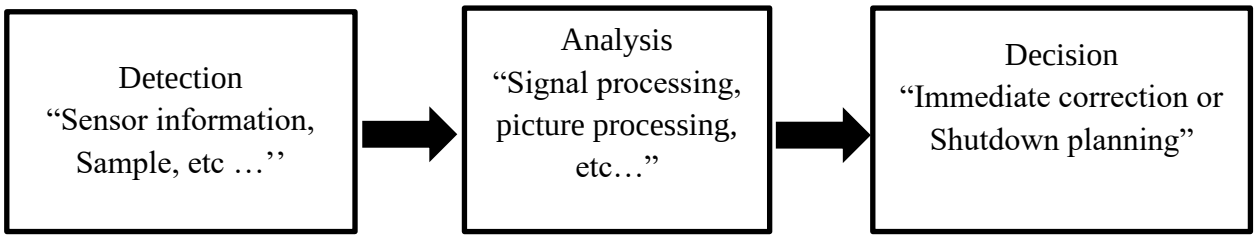


Figure 1-12 Steps for implementing predictive maintenance

1.5.1.14 Advantages of the predictive maintenance technique[4]

- Minimizes or eliminates costly downtime - increases profitable uptime.
- Minimizes or eliminates catastrophic machinery failures.
- Reduces maintenance costs.
- Reduces unscheduled maintenance - repairs can be made on time that least affect production.
- Reduces spare parts inventories - many parts can be purchased just in time for repairs to be made during scheduled machinery shutdowns.
- Minimizes or eliminates the possibility that machinery repairs were the wrong repairs.
- Reduces repair time and unnecessary repairs
- Reduces penalties that result from late deliveries caused by broken down or poorly performing machinery.
- Reduces warranty claims due to poor product quality caused by poorly performing machinery.
- Reduces the possibility of accepting recently purchased new or used machinery with defects
- Increases machinery safety - injuries are often caused by poorly performing machinery.

1.5.1.15 Disadvantages of the predictive maintenance technique[4]

- Increases investment in diagnostic equipment.
- Increases investment in staff training.
- Savings potential not readily seen by management.

1.6 Conclusion

This chapter, is an overview about Hassi Rmel region and its importance in the production of gas and its derivatives. Then, we delved into the various predictive maintenance tools currently used there.

2 nd Chapter General overview of centrifugal compressors

2.1 Introduction

A compressor is a machine whose function is to raise the pressure of the compressible fluid which through its name translates the fact that the fluid compresses (its volume decreases) as the pressure increases.

Gases being compressible fluids require compressors, while incompressible liquids require pumps for very low compression rates.

2.2 Compressors classification

Compressors can be classified according to several characteristics according to:

- the principle of operation (volumetric, turbocharger)
- the movement of moving parts (linear, rotary movement)
- the nature of the fluids

In general, there are two major compressor families, positive displacement compressors and dynamic compressors.

In the former, the pressure rise is obtained by reducing some volume of gas by mechanical action , and in the latter , increase the pressure by continuously converting the kinetic energy communicated to the gas into pressure energy due to the flow in the compression stage (impeller + diffuser).

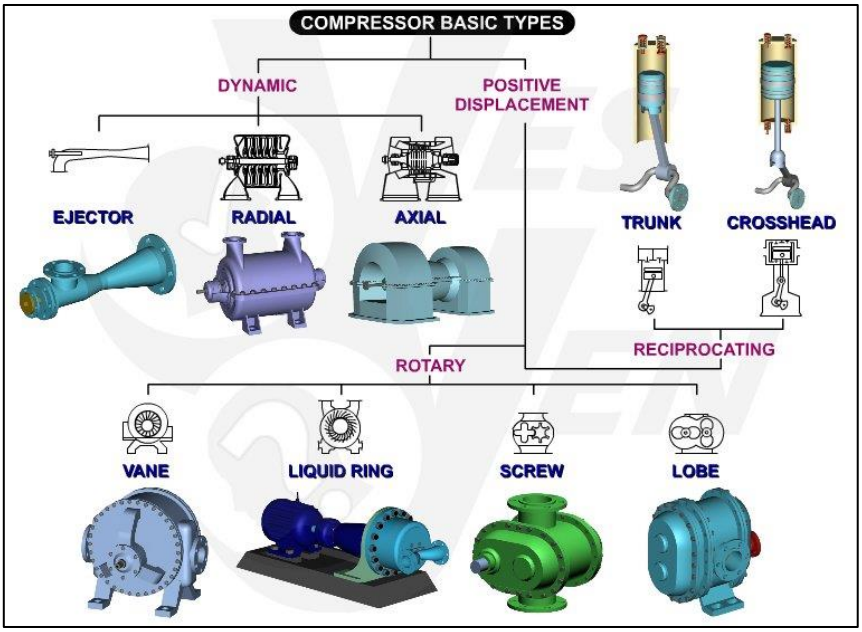


Figure 2.1 Basic types of compressors

2.2.1.1 Centrifugal compressors "radial ", Definition

Centrifugal compressor is a dynamic machine with continuous fluid flow.

Impellers attached to the shaft provide energy to the latter, part of this energy is transformed into pressure increase directly in the impeller, the rest in the stator, ie in the diffusers. [2]

2.2.1.2 Description of centrifugal compressors

This type of machine consists of an external body (casing) containing the part of the stator called diaphragm assembly (bundle) where a rotor formed by a:

- shaft and one or more impeller
- the balancing drum
- the thrust collar.
- Coupling hub.
- Seal cartridge

The rotor rotates on journal bearing, and it is kept in its axial position by the thrust bearing. [2]

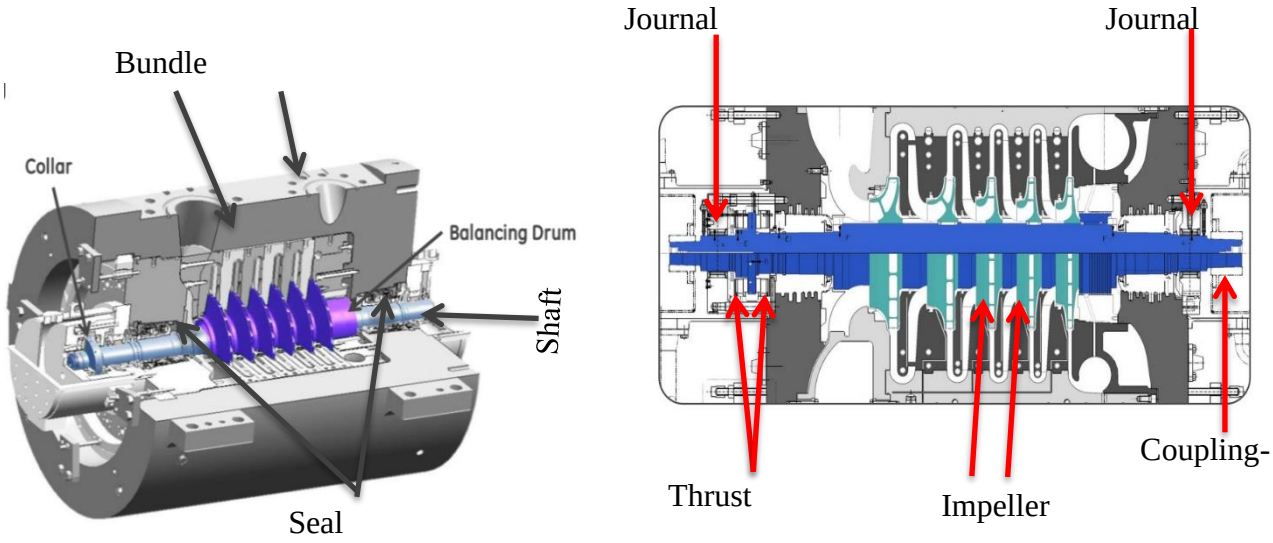


Figure 2.2 Different components of a centrifugal compressor

2.2.1.3 Centrifugal compressors compenents

There are two categories of compressor components:

- Rotating parts
- Fixed parts

Despite the variety of centrifugal compressors, the components are generally the same.

2.2.1.4 Rotating parts

All the components assembled on the shaft are identified as a rotating part.

The coupling hub, balance drum, spacers, impellers, and thrust collar are all part of this.

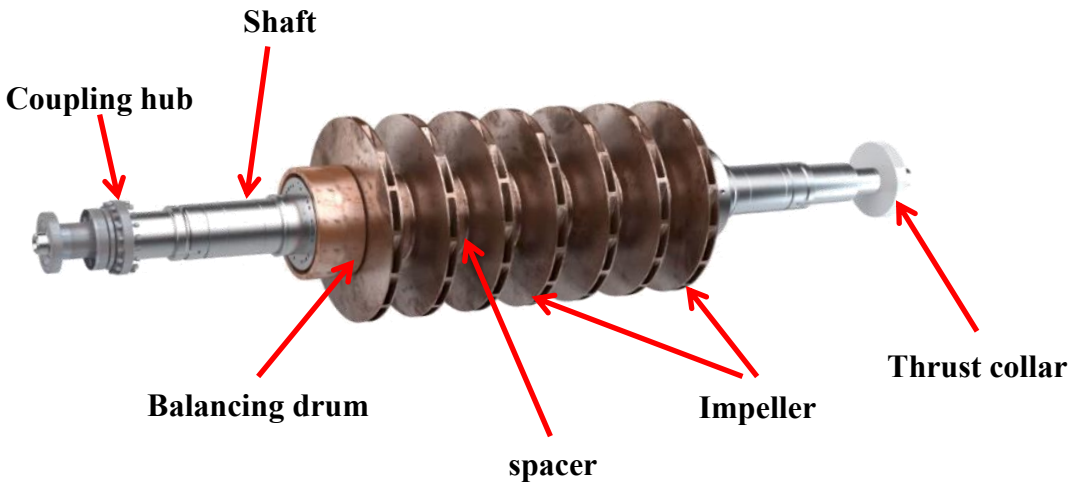


Figure 2.3 Rotating parts

2.2.1.4.1 Shaft

The shaft (Figure 2.4) in a centrifugal compressor is a crucial component that serves as the main rotating element. It typically connects the compressor's driver, such as an electric motor or a turbine, to the impeller(s) inside the compressor casing. The shaft is responsible for transmitting mechanical power from the driver to the impeller(s), allowing them to rotate and compress the gas or fluid being processed.

Shafts in centrifugal compressors are often made of high-strength materials such as alloy steel or stainless steel to withstand the high rotational speeds and loads encountered during operation. They are precision-engineered to maintain dimensional accuracy and balance, ensuring smooth and efficient operation of the compressor.

Additionally, the shaft may incorporate features such as keyways, threads, and mounting surfaces to facilitate the connection with other compressor components, such as impellers, balance drums, and bearings. Bearings are typically installed along the length of the shaft to support and guide its rotation, minimizing friction and wear.

Overall, the shaft plays a critical role in the performance and reliability of centrifugal compressors, as it transfers power and rotational motion from the driver to the compressor's internal components, enabling the compression process to take place efficiently.

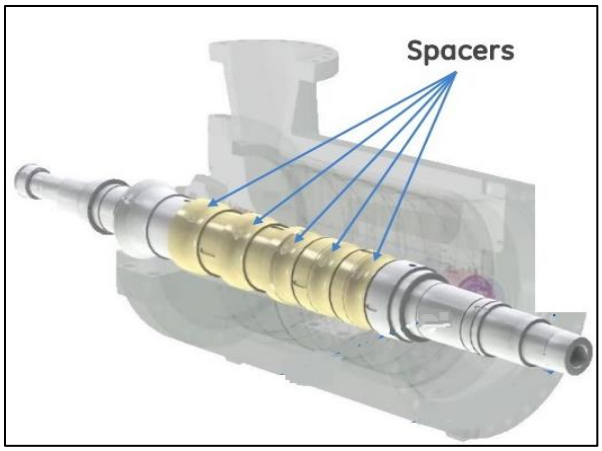


Figure 2.4 Shaft without impellers

2.2.1.4.2 Thrust collar

The thrust collar transmits the rotor thrust to the thrust bearings and fixes the axial position of the rotor.

It is hydraulically shrink-fitted to the shaft which makes the assembly/disassembly procedure easier to perform.

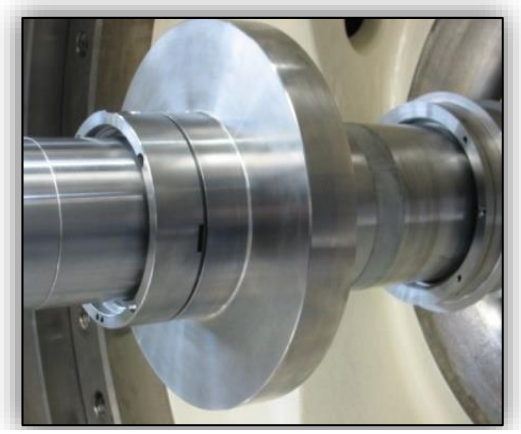
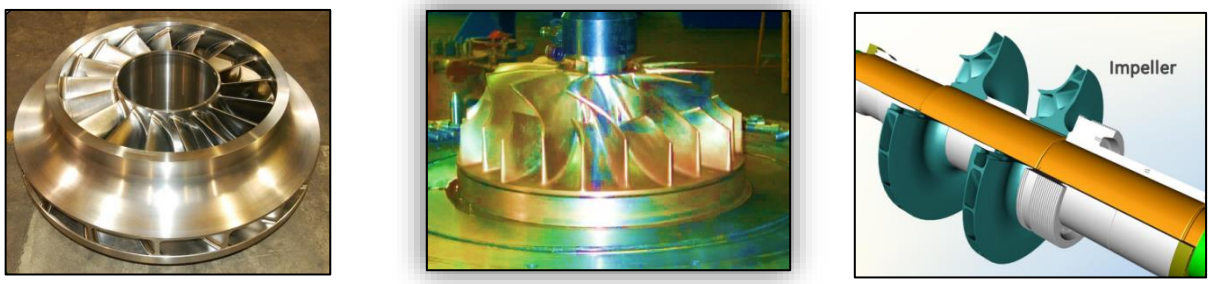


Figure 2.5 Thrust collar

2.2.1.4.3 Impeller

The impellers increase the gas's energy level. Depending on the needs of a specific application, impellers can be designed as open or closed systems, featuring various blade shapes. Closed impellers consist of a hub, blades, and a cover or shroud, while open impellers only include a hub and blades without a shroud. The manufacturing of impellers is carried out using either the Full Milling or Electrical Discharge Method. After manufacturing, each impeller undergoes balancing and testing at overspeed in a vacuum chamber to ensure its integrity. It is then subjected to dimensional checks and dye penetrant testing once more. Balancing of each impeller is performed at low speeds, with material being removed by grinding or weight being added until the final balance indications fall within the acceptable range. The overspeed test lasts for approximately five minutes and verifies the impeller's physical integrity under high-speed conditions exceeding the maximum continuous speed. This test is conducted individually on each impeller in a vacuum environment.



(a) (b) (c)

Figure 2.6 Impellers, (a): Closed impeller, (b): Opened impeller , (c): Assembled (shaft-*impeller)*

2.2.1.4.4 Balance drum

The balance drum, made of steel, is positioned after the last impeller. It is securely fitted onto the shaft through interference fitting and keying. On one side, it features threaded holes to aid in rotor balancing. The primary role of the balance drum is to counterbalance the majority of the axial thrust generated within the compressor.

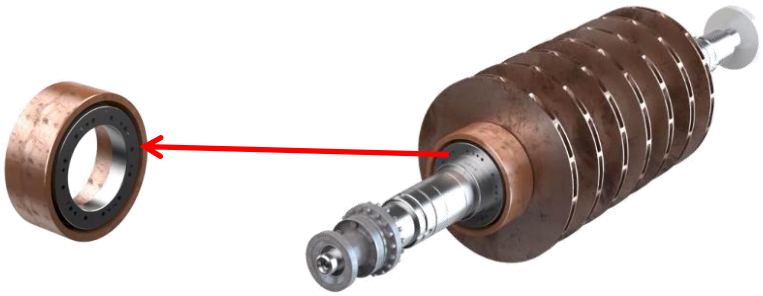


Figure 2.7 Balance drum

2.2.1.4.5 Coupling

A coupling is a mechanical device used to connect two shafts together at their ends for the purpose of transmitting power. Couplings allow for the transfer of motion and torque from one shaft to another while compensating for misalignment, vibration, and other factors.

It consists of three main components: Two coupling hubs, one for driver side & other for the driven side, and a spacer.

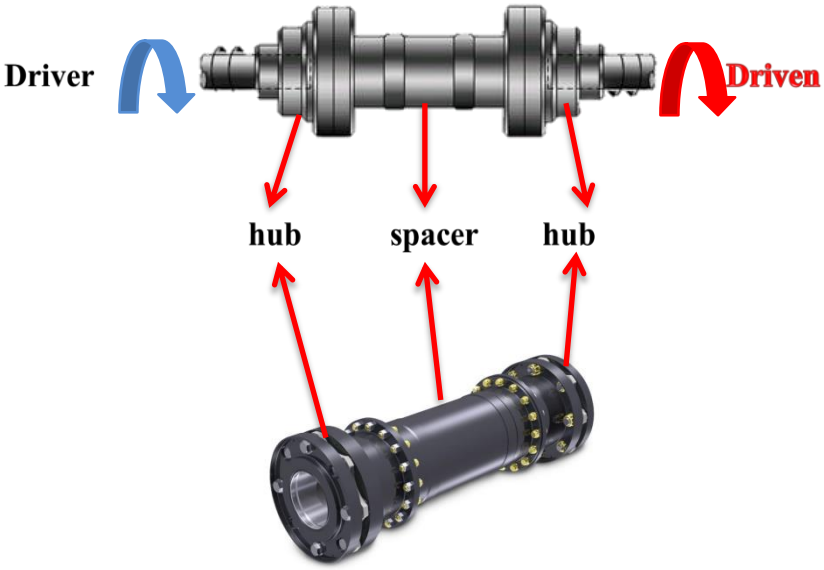
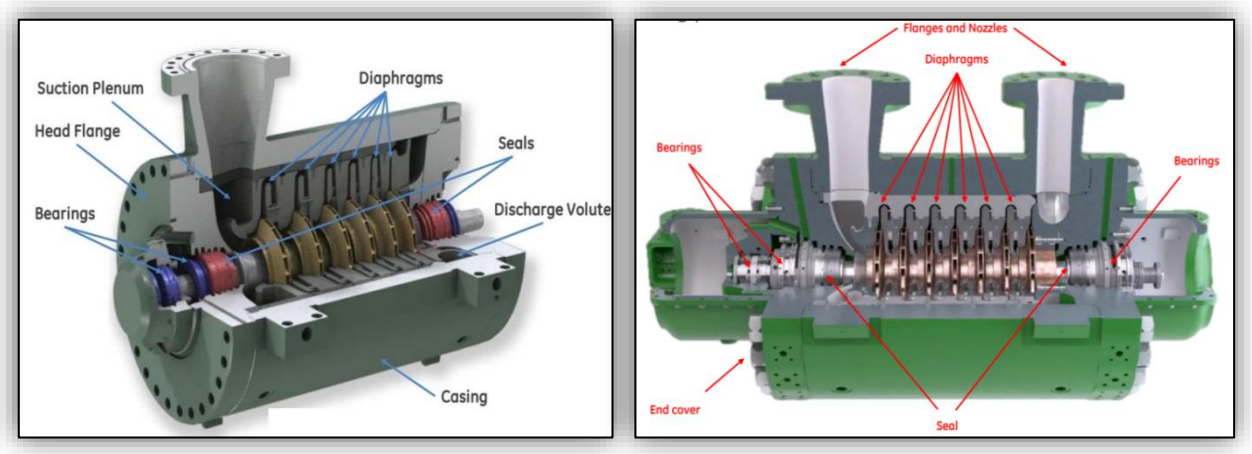


Figure 2.8 Coupling assembled

2.2.1.5 Fixed parts

It consists of: casing, diaphragms, journal & thrust bearings, seals, discharge volute and end cover.



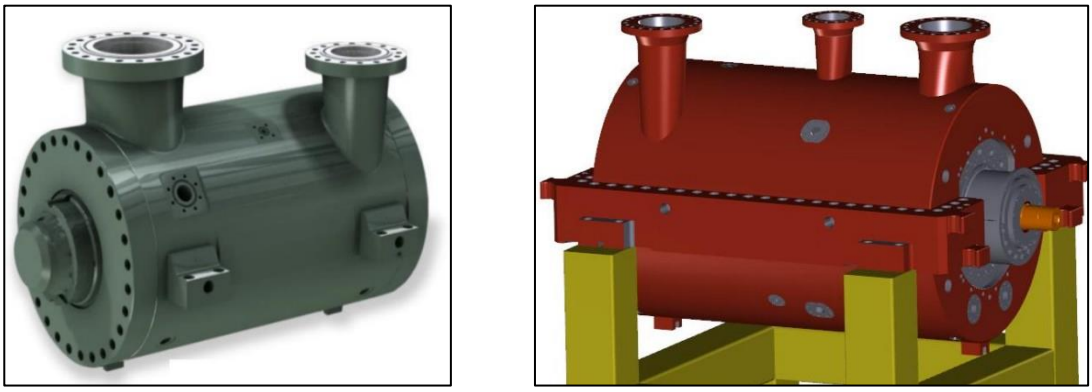
(a) (b)

Figure 2.9 Fixed parts, (a)3D description, (b)2D description

2.2.1.5.1 Casing

The casing is the outer shell of the centrifugal compressor that houses the internal components, such as the impellers, bearings, and shaft. It is designed to withstand the pressures and mechanical forces generated during the operation of the compressor. The casing can be made from various materials, such as steel, cast iron, or aluminum, depending on the requirements of the application and operating environment.

Centrifugal compressors may have casings of different shapes and sizes depending on their specific design and application. Some compressors have horizontally split casings, where the casing is divided into two halves that are assembled along the horizontal centerline. Other compressors may have vertically split casings, where the casing is divided into two halves assembled along the vertical centerline.



(a) (b)

Figure 2.10: Casing, (a) Horizontally split casing,(b) Vertically split casing

2.2.1.5.2 diaphragms

According to the number of impellers, diaphragms are obtained, whose role is to construct the gas path. They also construct the diffusers where the gas pressure increases through energy exchange.

Additionally, stator blades can be included to reduce turbulence in each impeller.



(a) (b)

Figure 2.11 Diaphragms, (a)Disassembled diaphragms, (b) Mounted

2.2.1.5.3 Bearings

Bearings are divided in two categories (Figure 2.12)

- Journal bearings:
- Thrust bearings:

Centrifugal compressors contain two journal bearings, one on the suction side and another on the discharge side. They also include two thrust bearings: one active and one inactive.

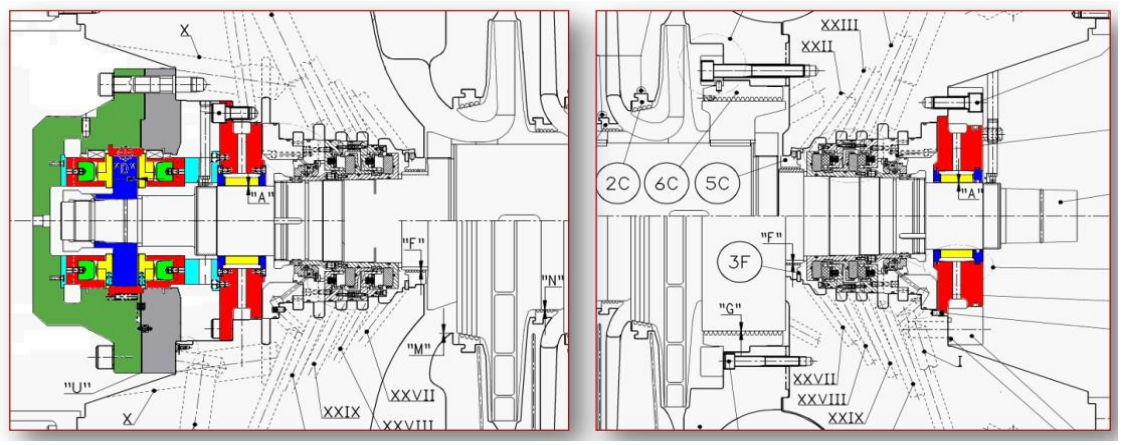


Figure 2.12 Drawing of journal and thrust bearings mounted in the CECO

2.2.1.5.4 Journal bearings

The journal bearing (Figure 2.13) serves the following functions:

- Supporting the weight of the rotor
- Generating a lifting effect with the lubricating oil
- Providing damping effects

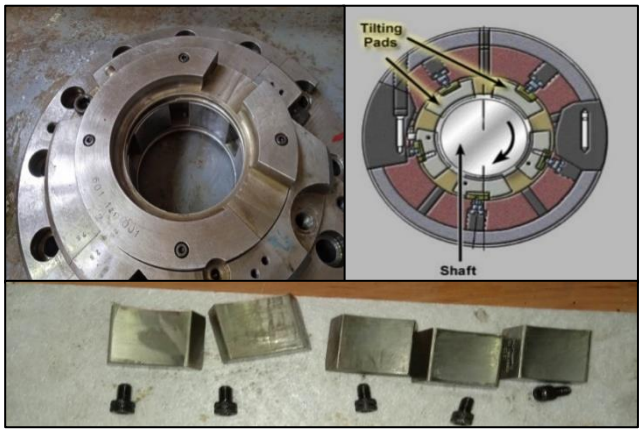


Figure 2.13 Journal bearings with titing pads

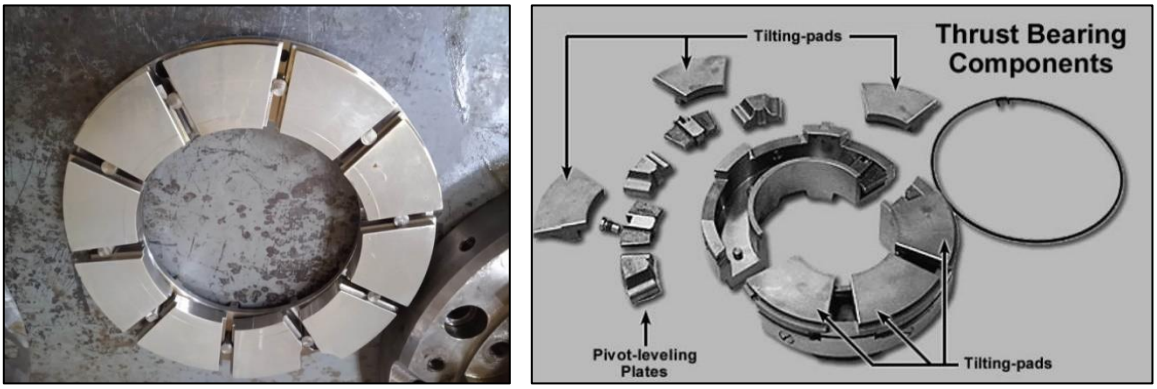
2.2.1.5.5 Thrust bearings

The function of the thrust bearing is to compensate part of the axial thrust.

If the compressor is operating properly the Inactive part is under the effect of the axial thrust during transient operation.

Both Active and Inactive side are exactly the same.

The Thrust bearing type used is called ‘Double acting self-equalizing’ because the load is equally distributed among the pads.



(a) (b)

Figure 2.14 Thrust bearing, (a) Assembled thrust bearing, (b) Thrust bearing component

2.2.1.5.6 Seals cartridges

Seals cartridges also are divided in two categories, when we can’t find them in the same compressor:

- Dry gas seal: contain with two parts: stator part and rotor part.
- Oil seal: all its components are fixed.

Their main function is to avoid external leakage.



(a) (b)

Figure 2.15 Seals cartridges, (a)Dry gas seal, (b)Oil seal.

2.2.1.6 How does it work ? " gas path "

2.2.1.7 Suction

Starting from the suction end we can say that the gas flow from the pipe arrives at the suction stage traveling in a radial direction and must be reoriented into an axial direction to enter the impeller.

The purpose of the suction stage is to convey the gas into the first impeller with low load losses and with uniform pressure and velocity.

Usually, the suction stage has a fin positioned at the opposite side of the suction flange, which splits the flow of the gas to avoid gas recycling in the inlet volute.

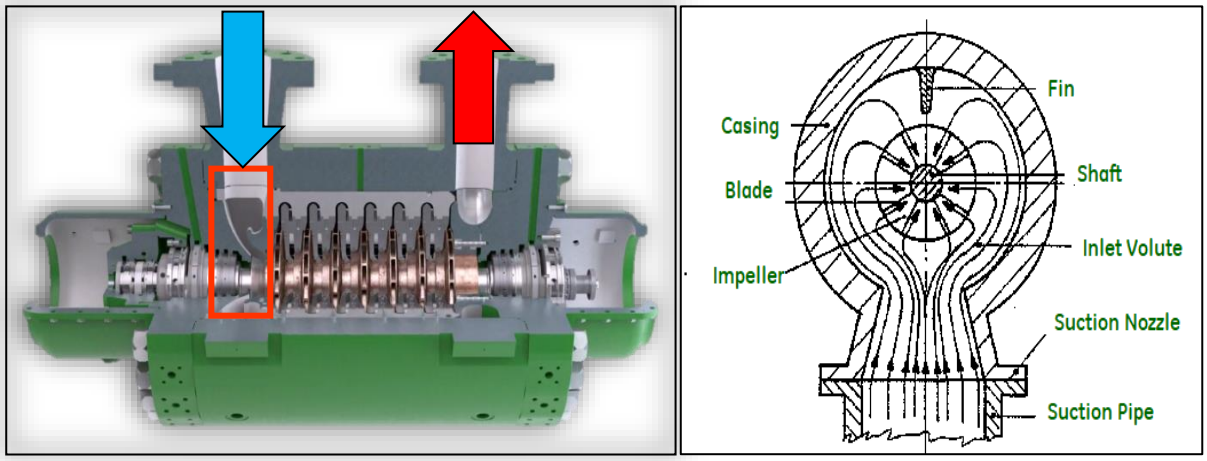


Figure 2.16 Distribution of the gas in the suction stage

2.2.1.8 Intermediate stages

The intermediate stages are the stages between the suction and the discharge; their number depends on how many impellers are installed on the shaft.

Due to the fact that each compressor is fully customized, the geometry of the intermediate stages will change from compressor to compressor, according to operating specifications.

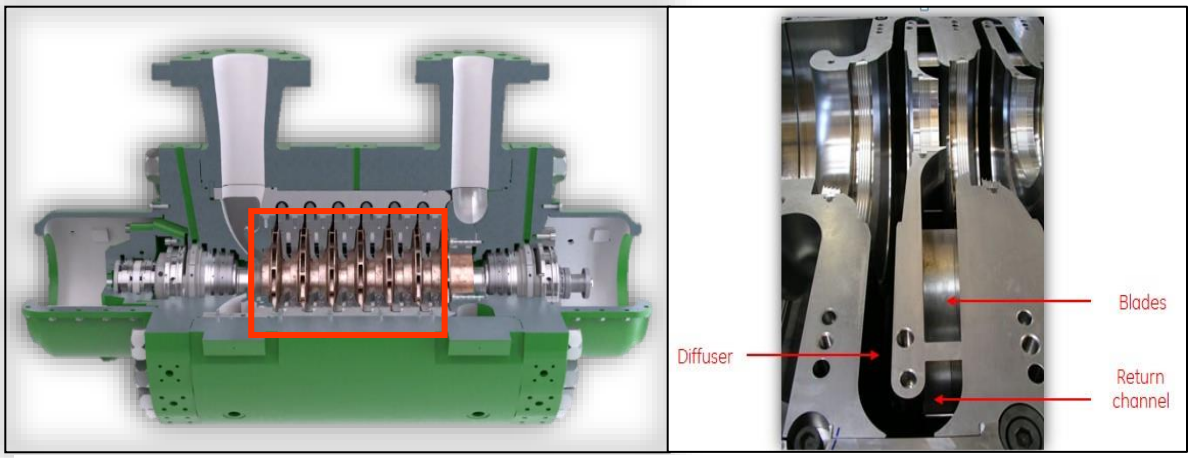


Figure 2.17 Intermediate stages design

2.2.1.9 Compression stage

A compressor stage consists of the impeller, the diffuser and the return channel.

The impeller rotates with the shaft, increasing both the velocity and the pressure of the gas.

Regarding the pressure increase, we can say that it occurs within the impeller and the diffuser, and that the magnitude of this increase depends on the design of both of these.

As shown in this diagram: in the impeller both the velocity and pressure increase; in the diffuser the pressure increases and the velocity decreases due to the convergent design; and in the return channel there is no increase in pressure because the convergent design is chosen only to avoid load losses.

The return channel is bladed in order to more effectively convey the gas toward the next impeller inlet, thus reducing load losses, but there is no further increase of pressure downstream the diffuser outlet.

We can state that all the pressure increase realized within a compressor stage is made between the blade inlet and the diffuser outlet.



Figure 2.18 Diagram evolution of "energy, pressure and velocity" in one stage

2.2.1.10 Discharge volute

The discharge section of the gas path is the connection between the inner parts of the compressor and the piping. The most important part is the Discharge volute.

The discharge volute is installed after the last diffuser and conveys the gas into the discharge piping.

The volute has a variable section to impart low load losses to avoid decreasing the pressure.

A fin is usually installed near the discharge flange to prevent gas recirculation within the volute.

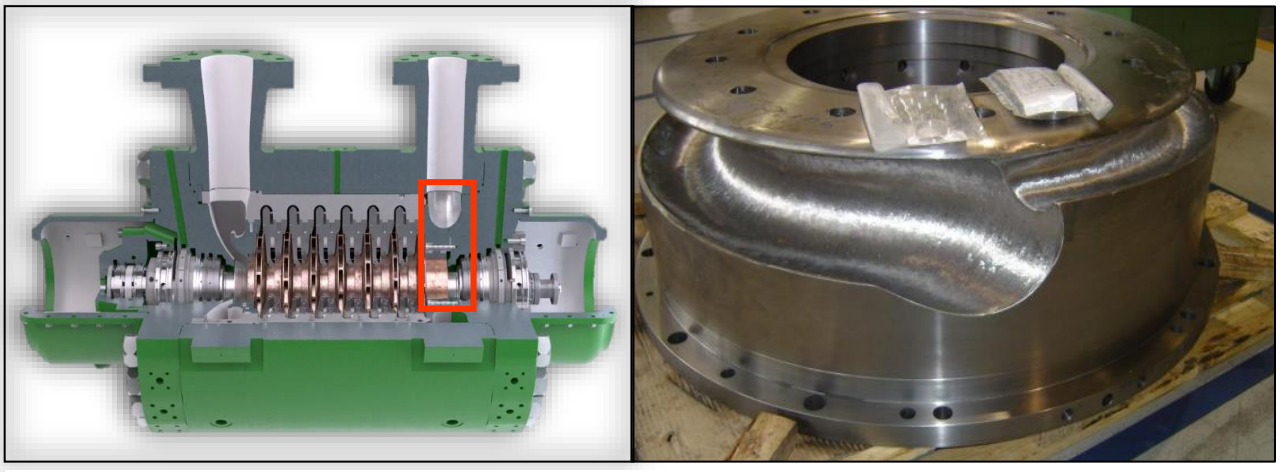


Figure 2.19 Discharge volute '' position & design ''

2.2.1.11 Undesirable phenomena during operation

The most Undesirable phenomena during the operation of centrifugal compressors:

- Radial vibration
- Thrust axial
- Surge

To safeguard the centrifugal compressor from these phenomena, it's crucial to comprehend the mechanisms behind each one.

Firstly, we must comprehend the cause of these phenomena.

Secondly, we need to ascertain effective monitoring techniques.

Finally, we should determine strategies for protecting our machine during critical scenarios.

2.2.1.12 Radial vibration

Since we have another detailed chapter on vibrations, I will deal with this point superficially.

a vibration is created when the mass is moved from its equilibrium position to a maximum or minimum position. If one considers that the movement is not dampened, the mass will vibrate indefinitely between its two positions maximum and minimum.

Causes: unbalance, misalignment, wear, fixation fault, critical speed, journal bearings faults ,…. Others

2.2.1.13 Axial thrust

During operation, an axial thrust is generated inside the compressor along the entire length of the rotor.

This axial thrust is caused mainly by pressures acting against the impellers (Figure 2.20).

The disc side of the impeller is exposed to discharge pressure, while the hub side is exposed partly to the discharge pressure and partly to suction pressure.

This pressure distribution generates a force normally in the direction of suction. The total value of this axial force depends on pressure levels and the surface area of the impeller upon which these pressures act.

Because these forces do not mutually compensate each other,

an axial load is generated upon the compressor rotor.

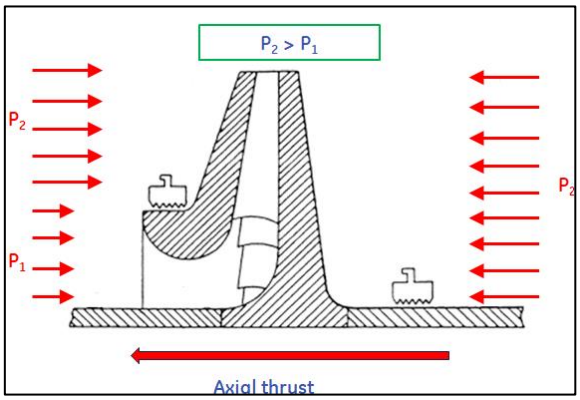


Figure 2.20 Axial thrust in one impeller

In multistage, high-pressure compressors this axial load may reach a very high value.

To compensate for axial load, the thrust bearing is always installed on all compressors.

Additionally, to reduce the axial load applied to the thrust bearing to a more convenient value, and also to reduce the size of the thrust collar which is an overhang mass often, a balancing drum is provided.

This balancing drum is placed after the last impeller of the rotor, at the discharge end of the compressor.

One side of the balance drum is exposed to discharge pressure, while the other side is exposed to suction pressure through a balancing line connected to the suction volute.

The diameter of the balance drum is designed to produce a thrust from the suction side to the discharge side of the compressor.

This reduces the load coming from impellers that is placed upon the thrust bearing.

The compensation normally is not complete, thus avoiding any axial instability in the rotor.

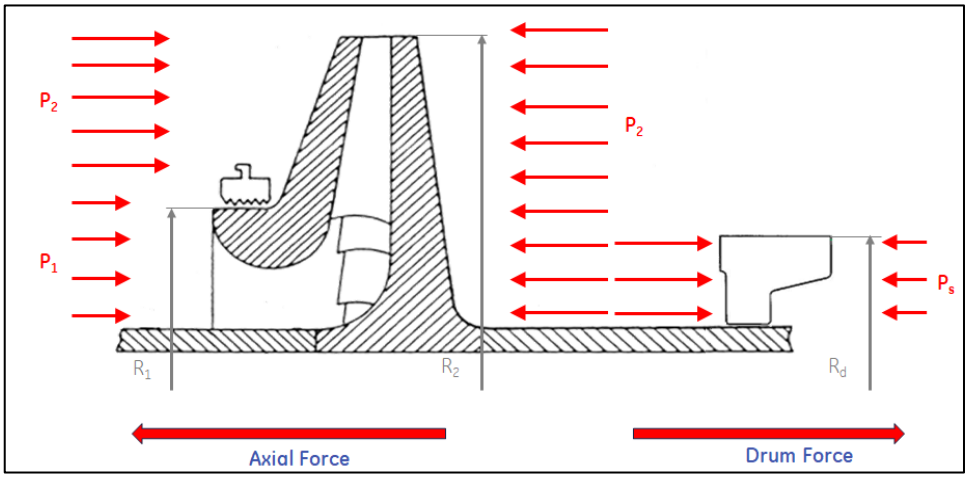


Figure 2.21 Role of balancing drum in balancing of axial thrust

2.2.1.14 Surge

Compressor surge is a form of aerodynamic instability in centrifugal compressors. The term describes violent gas flow oscillating in the axial direction of the compressor.

Surge occurs when there is no forward flow of gas through the compressor, leading to a reversal of flow.

During surge, the gas being compressed is pushed backward through the centrifugal compressor.

This phenomenon happens in milliseconds, causing the rotor to shift within its normal running position.

2.2.1.14.1 Causes of Compressor Surge

Surge can result from various factors, including:

Driver failure

Misdistribution of load in the compressor

Power failure

Upset process conditions

Failure of anti-surge mechanisms

High rotation speed with insufficient flow

2.2.1.14.2 Consequences of Centrifugal Compressor Surge

Surge has mechanical implications, affecting components such as ball bearings, seals, thrust bearings, and impellers.

Excessive vibrations during surge can lead to fractures in machinery parts.

Other consequences include:

Process-related problems causing plant shutdown

Increased compressor inlet temperature due to hot compressed gas returning at the inlet

Severe dynamic forces on the impeller and blade

Damage to bearings and gear teeth in the connected gearbox.

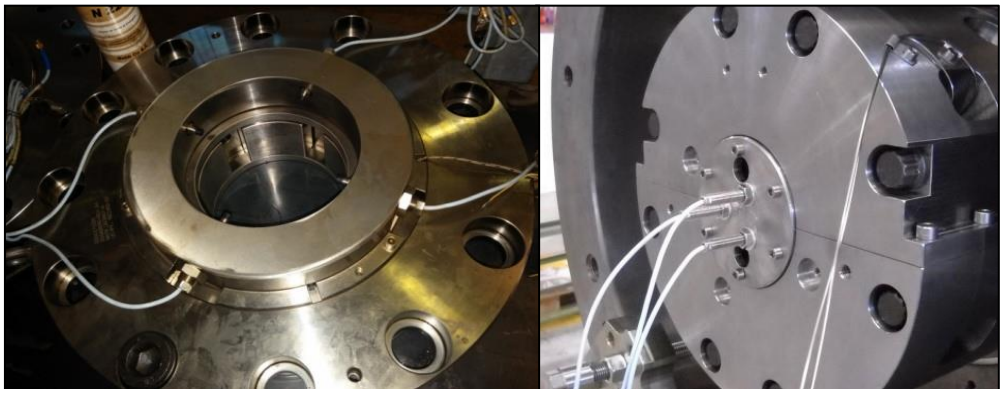
2.2.1.15 Monitoring & control

During operation, to monitor the effects on the compressor, axial displacement and radial vibration probes are used.

Both are Non-contacting probes, working with the eddy current principles, and usually connected to a system called 'Bently Nevada' for monitoring.

Axial displacement probes are installed on the Thrust Bearing shaft end and are minimum 2.

Radial vibration probes are installed on each journal bearing and they work as a couple measuring vibration amplitudes on X and Y axis.



(a) (b)

Figure 2.22 Proximity probes installing in both "thrust & journal bearings " (a)Radial monitoring, (b) Axial monitoring

Also a anti-surge system is used to ensure more protection,

The Anti-surge System is composed by:

- Anti-surge Valve
- Instrumentation:
    - Flow indicator transmitter
    - Pressure indicator transmitter
    - Electronic controller

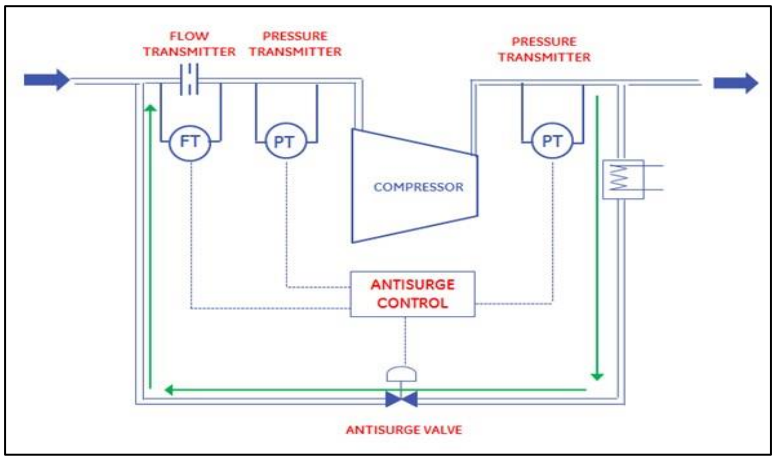


Figure 2.23 Anti-surge system

To avoid surge, the pressure transmitter of discharge sent a signal to anti-surge valve , this latter open and compensate the Insufficient of flow at the suction ,when the anti-surge valve we call it ‘’ the recycling state ‘’.

2.2.1.16 Tag name and centrifugal compressors types ‘’GENERAL ELECTRIC NUEVO PIGNONE – GE NP ‘’

Because our case of study is about a GE NP Centrifugal compressor, we need to know how does it tag their compressors,

Each GE NP centrifugal compressor is identified by a tag. The tag is divided into literal and numerical parts. Both parts of the tag give only general information about the machine.

Example: 2 MCL 806, BCL 405 /A, PCL 305, SRL.

2.2.1.17 Literal part:

the first letter identifies the type of the casing we have: B for Barrel type, M for middle split type, S for single volute, P for pipeline type.

The second letter identifies the type of the impeller we two type as we explain in impeller paragraph: C for closed, S for opened

The third letter identifies the type of diffuser: L i.e., free vortex ‘’without blades ‘’.

The letter appear with BCL types in the right side of the tag is particular to this type of compressors, it identifies Casing design pressure rating, it can be :

- **N** p<150 bar
- **A** p<200 bar
- **B** p<300 bar
- **C** p<400 bar
- **D** p<550 bar
- **E** p up to 1000 bar

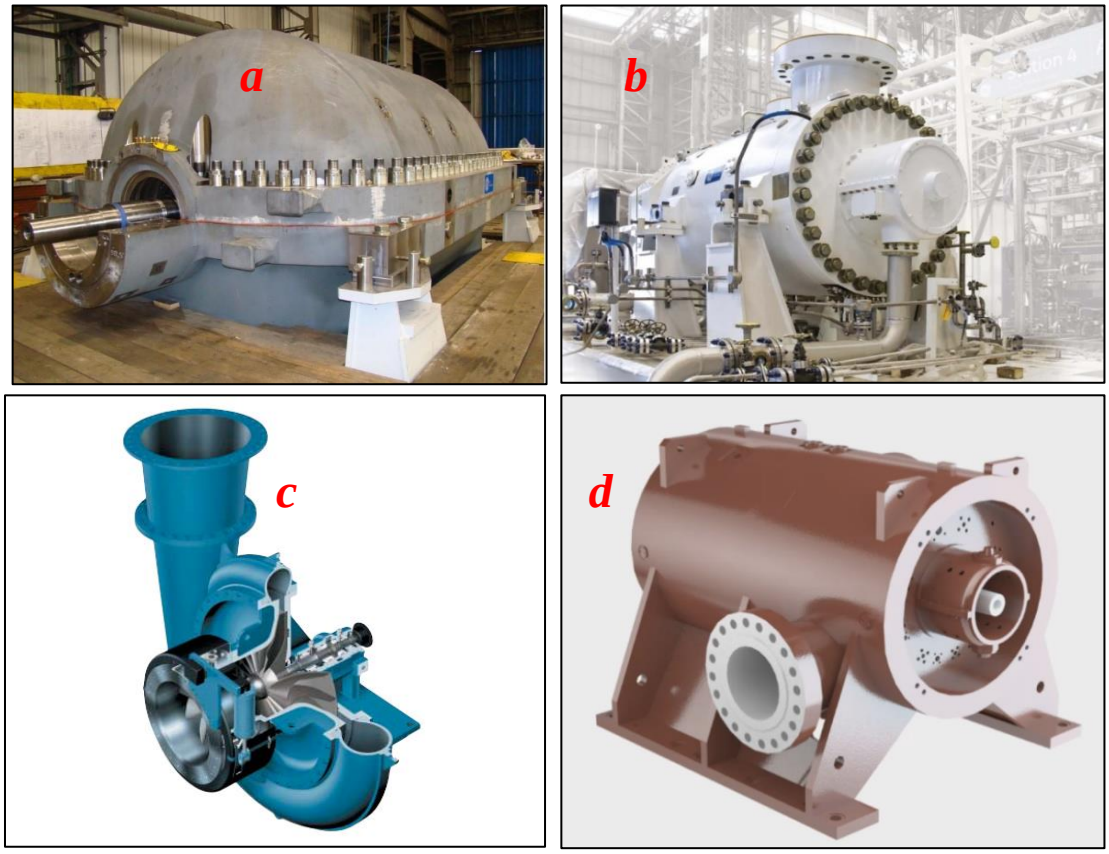


Figure 2.24 Types of the casing, a: Middle split, b: Barrel type, c: Single volute, D: pipeline type

2.2.1.18 Numerical part:

The numerical part of the compressor tag gives us information about the Section arrangement, Nominal impeller size and number of impellers or compression stages.

The first numerical value before letter identifies the section arrangement, it means a special configuration, it can be 2,3 or letter D

2: i.e. that the centrifugal compressor is made of 2 compressor section. Within this two compressor sections the impellers are installed on the shaft following a Back-to-Back configuration and we will have 2 suction and 2 discharge nozzles.

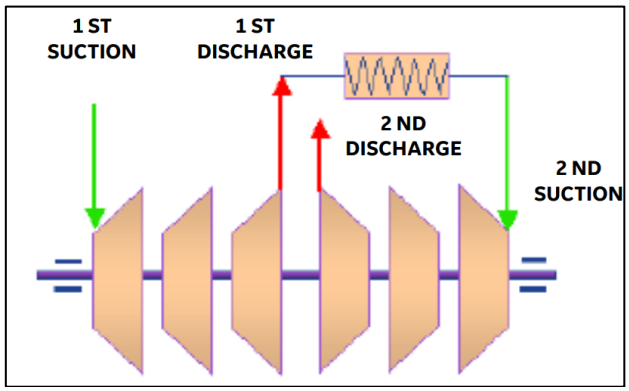


Figure 2.25 Section arrangement configuration « 2 »

3:i.e. that the centrifugal compressor is made of more than 1 compressor section. Within this compressor sections the impellers are installed on the shaft following an In-Line configuration and we will have 1 suction and 1 discharge nozzle plus one or more sidestreams

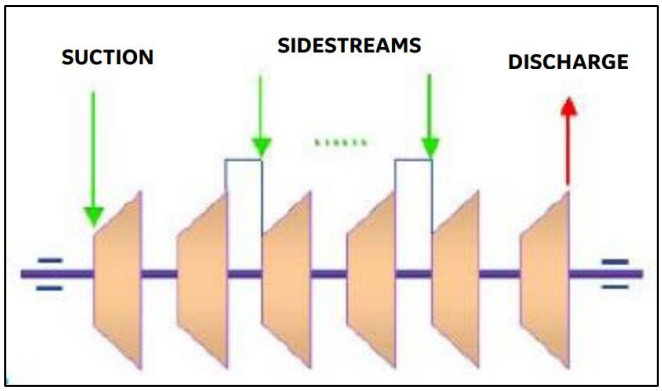


Figure 2.26 Section arrangement configuration« 3 »

D: i.e. that the centrifugal compressor is made of 2 compressor sections. Within this compressor sections the impellers are installed on the shaft following a Back-to-Back configuration and we will have 2 suction nozzles and 1 common discharge nozzle.

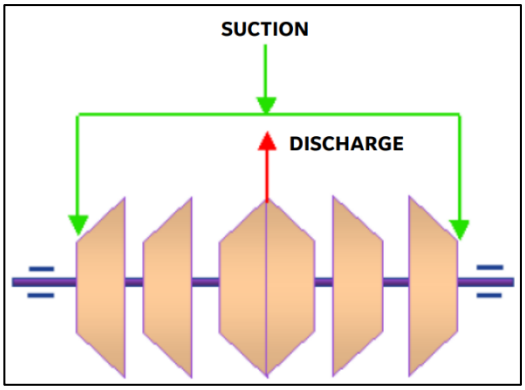


Figure 2.27 Section arrangement configuration « D »

The numerical value after letter identifies nominal impeller size, and the last number identifies the number of impellers, example: MCL 806 , i.e. 800 mm nominal impeller size and 6 is the number of impellers.

2.3 Conclusion

This chapter is a set of definitions about centrifugal compressors, their types (BCL, MCL, …etc) and their components (rotor, impellers, bearings, etc.), as well as the undesirable phenomena encountered during their operation. Its objective is to provide an overview of centrifugal compressors.

3 rd Chapter Vibration analysis and signal processing

3.1 Introduction

All rotating machines in operation produce vibrations. The deterioration of the functioning, resulting in a «change of dynamic energy disposition»,

Often leads to an increase in vibratory level. By analyzing the evolution of the latter, it is possible to obtain very relevant information about the functional state of the machine.

The use of vibration to monitor machinery is not new - since mechanics used to put their screwdrivers on an engine to "listen to internal movements—but these techniques have now significantly and greatly improved through equipment modernization, exponentially increasing the efficiency of contemporary maintenance[8].

3.2 What is vibration?

The most classical example is that of a body with mass M to which a spring with a stiffness k is attached. Until a force is applied to the mass M and causes it to move, there is no vibration. Refer to Figure. By applying a force to the mass, the mass moves to the left, compressing the spring. When the mass is released, it moves back to its neutral position and then travels further right until the spring tension stops the mass. The mass then turns around and begins to travel leftwards again. It again crosses the neutral position and reaches the left limit. This motion can theoretically continue endlessly if there is no damping in the system and no external effects (such as friction) [9].

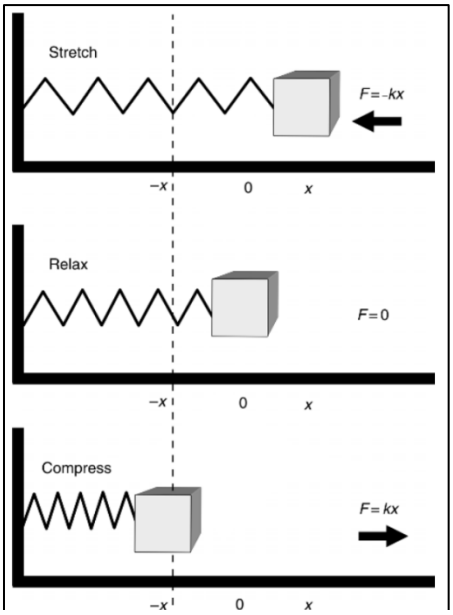


Figure 3-1 The nature of vibration

This motion is called vibration.

3.3 The nature of vibration

A lot can be learned about a machine's condition and possible mechanical problems by noting its vibration characteristics. We can now learn the characteristics, which characterize a vibration signal. Referring back to the mass-spring body, we can study the characteristics of vibration by plotting the movement of the mass with respect to time. This plot is shown in the Figure 3-2.

The motion of the mass from its neutral position, to the top limit of travel, back through its neutral position, to the bottom limit of travel and the return to its neutral position, represents one cycle of motion. This one cycle of motion contains all the information necessary to measure the vibration of this system. Continued motion of the mass will simply repeat the same cycle.

This motion is called periodic and harmonic, and the relationship between the displacement of the mass and time is expressed in the form of a sinusoidal equation:

$$X(t) = X_0 \sin(\omega t)$$

X = displacement at any given instant t;

X0 = maximum displacement;

$\omega = 2 \cdot \pi \cdot f$;

ω= is sometimes called the circular frequency (rd/s)

f = frequency (cycles/s – hertz – Hz);

t = time (seconds).

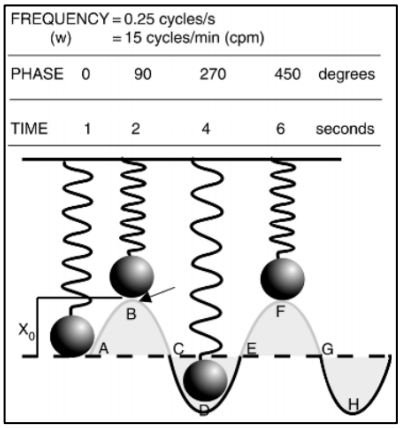


Figure 3-2 Simple harmonic wave – locus of spring-mass motion with respect to time

As the mass travels up and down, the velocity of the travel changes from zero to a maximum. Velocity can be obtained by time differentiating the displacement equation:

$$Velocity = V = \frac{dX}{dt} = X_0 . \omega . \cos(\omega t)$$

Similarly, the acceleration of the mass also varies and can be obtained by differentiating the velocity equation:

$$Acceleration = a = \frac{dV}{dt} = -X_0 . \omega^2 . \sin(\omega t)$$

In Figure 3-3: displacement is shown as a sine curve; velocity, as a cosine curve; acceleration is again represented by a sine curve.

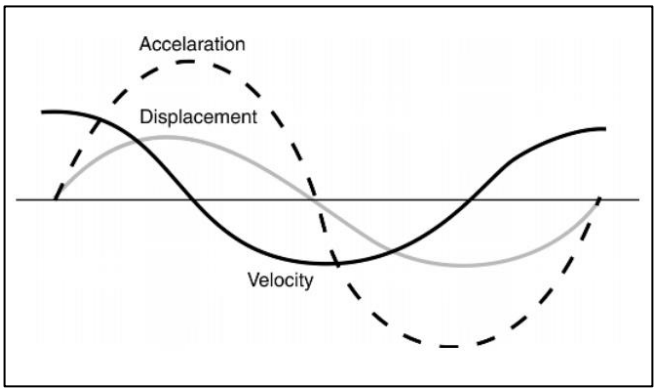


Figure 3-3 Waveform of acceleration, velocity and displacement of mass in simple harmonic motion

3.4 Wave fundamentals

Terms such as cycle, frequency, wavelength, amplitude and phase are frequently used when describing waveforms. We will now discuss these terms and others in detail as they are also used to describe vibration wave propagation.

We will also discuss waveforms, harmonics, Fourier transforms and overall vibration values, as these are concepts connected to machine diagnostics using vibration analysis. In the Figure 3-4 Comparison of waves with different amplitudes , waves 1 and 2 have equal frequencies and wavelengths but different amplitudes. The reference line (line of zero displacement) is the position at which a particle of matter would have been if it were not disturbed by the wave motion.

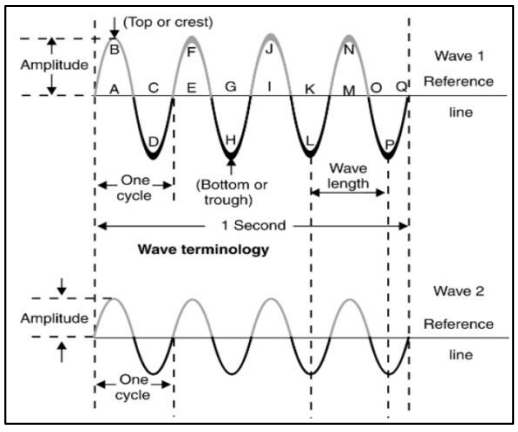


Figure 3-4 Comparison of waves with different amplitudes

3.4.1.1 Frequency (cycle)

Frequency is the repetition rate of vibration per unit of time.

At point E, the wave begins to repeat with a second cycle, which is completed at point I, a third cycle at point M, etc.

The peak of the positive alternation (maximum value above the line) is sometimes referred to as the top or **crest**, and the peak of the negative alternation (maximum value below the line) is sometimes called the bottom or trough, as shown in Figure 3-4. Therefore, one cycle has one crest and one trough.

The frequency (f) has units of cycles/second, or hertz (Hz) and is the reciprocal of the period in seconds

3.4.1.2 Wavelength

A wavelength is the distance in space occupied by one cycle of a transverse wave at any given instant. If the wave could be frozen and measured, the wavelength would be the distance from the leading edge of one cycle to the corresponding point on the next cycle. Wavelengths vary from a few hundredths of an millimeters at extremely high frequencies to many kilometers at extremely low frequencies, depending on the medium. In Figure 3-4 (wave 1), the distance between A and E, or B and F, etc., is one wavelength. The Greek letter λ (lambda) is commonly used to signify wavelength.

3.4.1.3 Amplitude

Two waves may have the same wavelength, but the crest of one may rise higher above the reference line than the crest of the other, for instance waves 1 and 2 in Figure 3-4.

The height of a wave crest above the reference line is called the amplitude of the wave. The amplitude of a wave gives a relative indication of the amount of energy the wave transmits.

A continuous series of waves, such as A through Q, having the same amplitude and wavelength, is called a train of waves or wave train.

3.4.1.4 Phase

If we consider the two waves as depicted in Figure 3-5, we find that the waves are identical in amplitude and frequency but a distance of T/4 offsets the crests of the waves. This lag of time is called the phase lag and is measured by the phase angle.

A time lag of T is a phase angle of 360°, thus a time lag of T/4 will be a phase angle of 90°. In this case we would normally describe the two waves as out of phase by 90°.

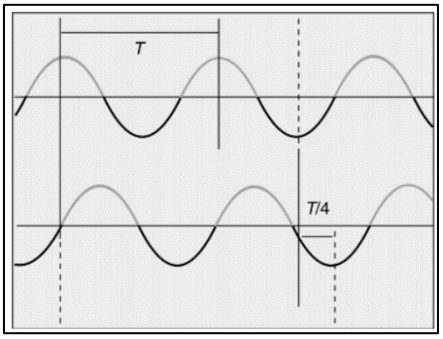


Figure 3-5 Phase relationship between two similar

3.4.1.5 Waveform

We have seen earlier, under the topic nature of vibrations, that displacement, velocity and acceleration of a spring-mass system in motion can be represented by sine and cosine waves. The waveform is a visual representation (or graph) of the instantaneous value of the motion plotted against time.

3.5 Monitoring & diagnostic tools

Monitoring tools are physical quantities used to monitor facilities.

Their evolutions make it possible to alert the technician of a deterioration of the operation without designating the defective element. [10]

There are:

- Time Domain, Scalar indicators or overall levels (OL);
- Frequency domain ‘’Spectrum ‘’.
- Orbital domain analysis
- Specific indictors

3.5.1.1 Time Domain

Vibration data, plotted as amplitude versus time, are referred to a time domain data profile. Examples of time domain are shown in Figure 2.5 . Time domain data are helpful in detecting some mechanical faults and sometimes it's so difficult to interpret the pattern since the time signal includes all kinematics and noise initiated in the machine during the measurement.

3.5.1.2 Peak amplitude (pk)

It represents the maximum amplitude of the signal relative to its equilibrium value.

$$A_p = \sqrt{\max\left[S^2(t)\right]}$$

3.5.1.3 Peak-to-peak amplitude (pk-pk)

It represents the difference between the extreme amplitudes of the signal for a given observation time.

$$A_{pp} = \max\left[S(t)\right] - \min\left[S(t)\right]$$

3.5.1.4 The effective amplitude Aeff or (Root Mean Square) RMS:

As in electricity, it represents the «static» corrected amplitude of the straightened signal, thus indicating the energy given by the vibratory movement. The maximum acceptable level is given, regardless of the machine, by the following formula:

$$RMS = \sqrt{\frac{1}{T}\int_0^T S^2(t)dt}$$

When: T: represents the period, the time to complete one cycle of vibration.

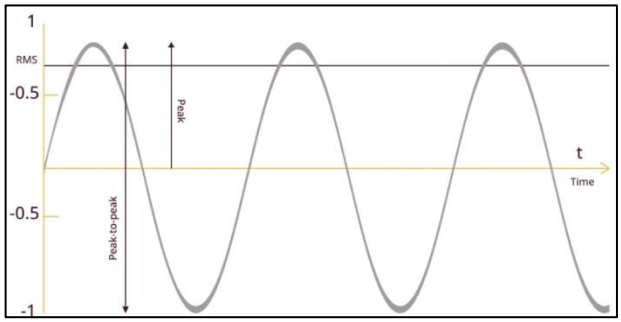


Figure 3-6 Three methods of amplitude measurement of a single-frequency (sine wave) signal.

Relation between A_p,A_{pp} & RMS :

- ✓ RMS = $A_p / \sqrt{2}$=0.707 A_p
- ✓ A_{pp}= $2\sqrt{2} \times RMS$= 2,828.RMS

$A_{pp}= 2 \times A_p$

according to the API ‘’american petroleum institute standard The maximum acceptable level is given, regardless of the machine, by the following formula :

$$A_{pp}\ \max = 25,4\sqrt{\frac{12000}{RPM}}$$

3.5.1.5 Effective velocity

This indicator is also indicative of the phenomena known as «low frequencies» (BF). These phenomena are the most energetic, and therefore the most destructive. They can also cause wear or cracks. An increase in unbalance, a lineage defect, will result in an abnormal increase in this indicator.

3.5.1.6 Effective acceleration

It is an indicator of the so-called «high frequency» (HF) phenomena such as bearing, gear defects... An abnormal acceleration rise is generally related to an advanced degradation of the bearings

3.6 Specific indictors

3.6.1.1 Crest factor

The major defect of this indicator is to present approximately the same values in the two extreme cases (new condition and end of life of the bearing). [11]

Only its evolution is significant. It is, however, a stable indicator.

$Crest\ Factor = Peak\ level\ /\ RMS$

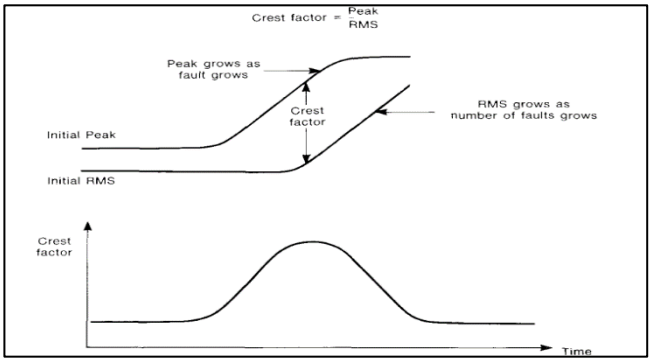


Figure 3-7 The Crest Factor principle

3.6.1.2 K-factor

The K-factor is safer for spot analysis of bearings. Its value is directly related to the condition of the bearings.

Because of its calculation mode (g^2) and contrary to the peak factor FC, the factor K is an unstable indicator.

$K = A_{pp} \times RMS$

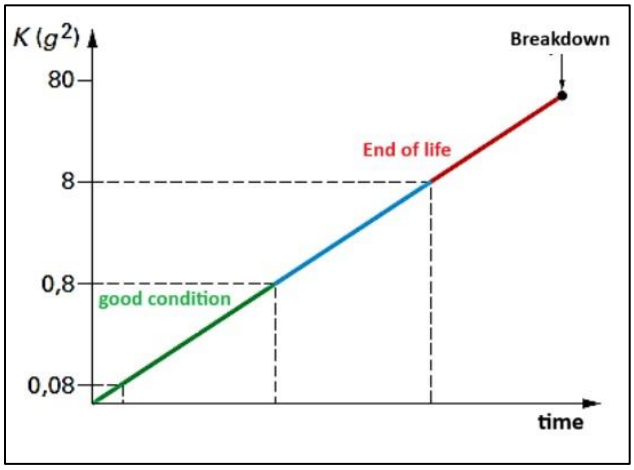


Figure 3-8 K-factor variation as a function of time

3.6.1.3 Frequency Domain

frequency domain displays how much of the signal exists within a given frequency band concerning a range of frequencies. The signature of frequency domain signal is displayed in Figure 3-9. A frequency-domain representation can include information on the phase shift that must be applied to each sinusoid to be able to recombine the frequency components to recover the original time signal

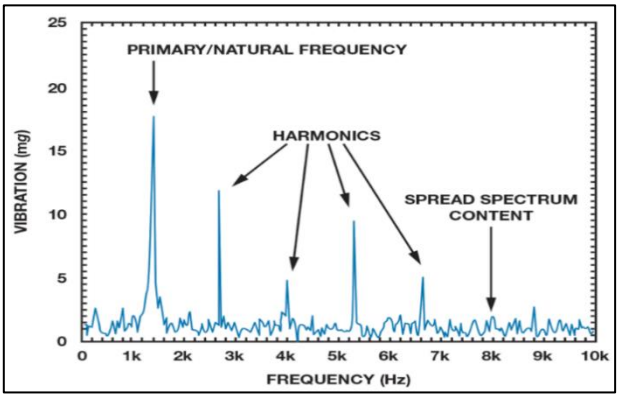


Figure 3-9 Typical frequency-domain vibration signature

Frequency-domain data are obtained by converting time domain data using a mathematical algorithm called fast Fourier transform (FFT). FFT allows each vibration component of a complex machine-train spectrum to be shown as a discrete frequency peak. The frequency-domain amplitude can be the displacement per unit time related to a particular frequency which is plotted on the y-axis against the frequency on the x-axis. The relation between the frequency and time domain is illustrated in Figure 3-10. [4]

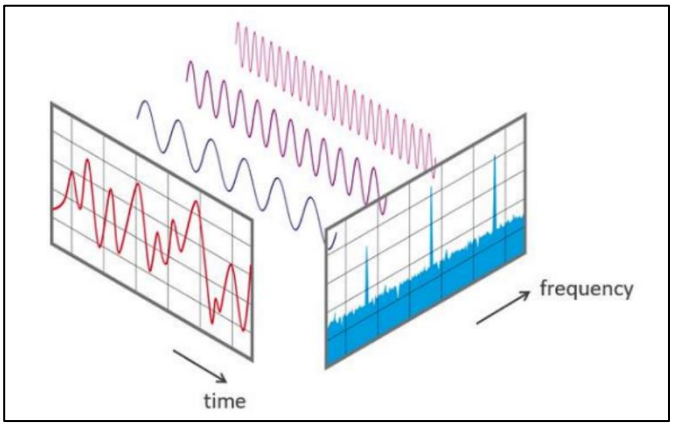


Figure 3-10 Relationship between time and frequency domain

3.6.1.4 Relation between DFT ‘’ Discrete Fourier transform ‘’ and FFT ‘’Fast Fourier Transforms ‘’

the Fast Fourier Transform (FFT) is an algorithm used to efficiently compute the Discrete Fourier Transform (DFT) of a sequence. In other words, the FFT is a specific implementation of the more general DFT algorithm. Here's how they are related:

Computational Efficiency: The FFT algorithm significantly reduces the number of arithmetic operations required to compute the DFT. While the direct computation of the DFT involves (N^2) operations, where N is the number of data points, the FFT algorithm reduces this complexity to (N log N) operations. This makes it much faster for large sequences.

Mathematical Equivalence: Despite the difference in computational complexity, the FFT computes the same result as the DFT. Both algorithms transform a sequence of complex-valued data points from the time domain to the frequency domain, providing information about the frequency content of the signal.

Inverse Transform: Just as the DFT has an inverse transform called the Inverse Discrete Fourier Transform (IDFT), the FFT algorithm has an inverse version called the Inverse FFT (IFFT). The IFFT computes the inverse DFT, allowing reconstruction of a time-domain signal from its frequency-domain representation.

Applications: While the DFT is a fundamental mathematical tool, the FFT algorithm is widely used in practice due to its computational efficiency. It is the preferred method for computing the DFT in applications such as audio signal processing, image processing, telecommunications, and many others.

3.6.1.5 Discrete Fourier transform ‘’mathematical relation ‘’

The discrete Fourier transform a sequence of N complex numbers ‘’time domain ‘’ $\{x_n\}= x_0, x_1,\ldots,x_{n-1}$ into another sequence of complex numbers ‘’ frequency domain ‘’ $\{X_n\}= X_0, X_1,\ldots,X_{n-1}$, which is defined by the following formula: [12]

$$X_k = \sum_{n=0}^{N-1} x_n . e^{-i2\pi \frac{k}{N} n}$$

This transform is sometimes denoted by the symbol $\mathcal{F}$, as in $\mathbf{X}=\mathcal{F}\{\mathbf{x}\}$ or $\mathcal{F}(\mathbf{x})$ or $\mathcal{F}\mathbf{x}$.

We can note that : $\omega^n = e^{-i2\pi \frac{n}{N}}$

So it became $X_k = \sum_{n=0}^{N-1} x_n . \omega^{kn}$

The result is a complex numbers & the matrix representation is , For k=0,1,…..,N-1

$$\underbrace{\begin{bmatrix} X_0 \\ X_1 \\ \vdots \\ \vdots \\ X_{(N-1)} \end{bmatrix}}_{frequency-domain} = \begin{bmatrix} \omega^0 & \omega^0 & \omega^0 & \cdots\cdots & \omega^{0(N-1)} \\ \omega^0 & \omega^1 & \omega^2 & \cdots\cdots & \omega^{1(N-1)} \\ \omega^0 & \omega^2 & \omega^4 & \cdots & \omega^{2(N-1)} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \omega^0 & \omega^{1(N-1)} & \omega^{2(N-1)} & \cdots\cdots & \omega^{(N-1)(N-1)} \\ [k=0 & k=1 & k=2 & & k=n-1] \end{bmatrix} \underbrace{\begin{bmatrix} x_0 \\ x_1 \\ \vdots \\ \vdots \\ x_{(N-1)} \end{bmatrix}}_{time-doa\,\min} ; \omega^0=1$$

The discrete Fourier transform requires a tremendous amount of calculations for digital signals with large numbers of points.

A time history with **M** coordinates would require $\mathbf{M^2}$ complex multiplication steps.

The discrete Fourier transform can be carried out by a Fast Fourier transform (FFT) method, however. The method is based on a time series with a number of points equal to $\mathbf{2^N}$, where **N** is an integer. The FFT requires **M log M** complex multiplication steps, where $\mathbf{M = 2^N}$.

The most efficient way to compute DFT is using the fast Fourier transforms algorithm or FFT

Example: consider a time history with 1,000,000 points,

DFT → require 10^{12} complex multiplication steps.

On the other hand

FFT → would only require approximately $2(10^7)$ steps.

3.6.1.6 Orbital domain analysis

The orbit represents the path of the shaft centerline relative to a pair of orthogonal eddy current transducers. These transducers are usually mounted rigidly on the machine casing near a bearing; thus, the orbit typically represents the path of the shaft centerline relative to the bearing clearance of the machine. The orbit is probably the most powerful single plot format available to the machinery diagnostician. [13]

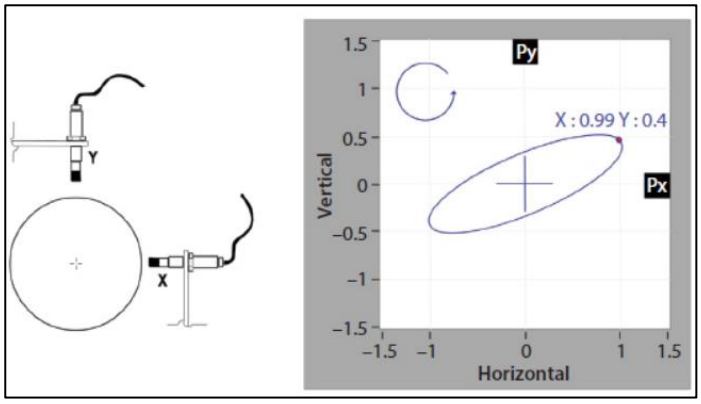


Figure 3-11 Orbit plot generated from two orthogonal proximity probe

3.6.1.7 Orbit Shape and its Fault Type

The malfunction of rotating machinery causes a variety of faults such as unbalance, shaft misalignment and oil whirl in a rotor shaft. It has been well studied that the fault types in a rotor dynamics have a corresponding orbit shapes. The representative corresponding orbit shapes are summarized in the following table. [14]

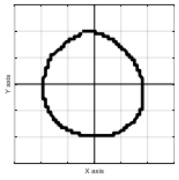
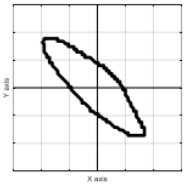
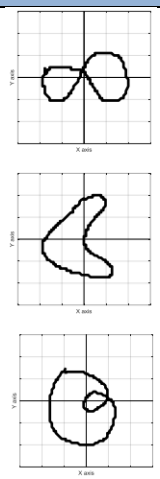
Fault	Normal	Unbalance	Shaft misalignment
Orbit shape			

table 3-1 Orbit shape and fault

3.7 Vibration Transducers[4]

3.7.1.1 Definition

A transducer is a device that converts one type of energy, such as vibration, into a different type of energy, usually an electric current or voltage. Commonly used transducers are velocity pickups, accelerometers and Eddy current or proximity probes. Each type of transducer has distinct advantages for certain applications, but they all have limitations as well. No single transducer satisfies all measurement needs. One of the most important considerations for any application is to select the transducer that is best suited for the job. The various vibration transducers are discussed below.

3.7.1.2 Types

As we said in ‘’ nature of vibration paragraph ‘’, vibrations can be expressed in displacement, velocity or acceleration, there are different types of transducers based on the parameters of vibration source

3.7.1.3 Proximity Probe

The Proximity Probe, also called an "Eddy Current Probe" or "Displacement Transducer", is a permanently mounted unit. It includes all sensors that perform non-contact detection in comparison to sensors, such as limit switches, that detect objects by physically contacting them. Proximity Sensors convert information on the movement or presence of an object into an electrical signal.

There are three types of detection systems that do this conversion:

- systems that use the eddy currents that are generated in metallic sensing objects by electromagnetic induction.
- systems that detect changes in electrical capacity when approaching the sensing object.
- systems that use magnets and reed switches.

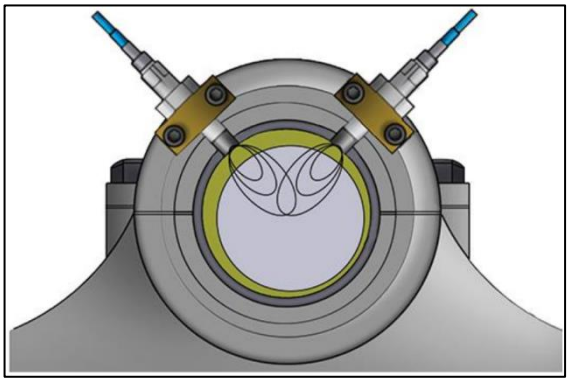


Figure 3-12 Orthogonal proximity probe

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3.7.1.3.1 Features

- Proximity sensors detect an object without touching it, and they therefore do not cause abrasion or damage to the object
- No contacts are used for output, so the Sensor has a longer service life (excluding sensors that use magnets). Proximity sensors are suitable for use in locations where water or oil is used.

- Proximity Sensors can be used in a wide temperature range.
- Proximity Sensors are not affected by colors

3.7.1.3.2 Limitations

- Proximity Probes are difficult to calibrate absolutely.
- A variation in magnetic properties of shaft and geometric irregularities of shaft gives erroneous signal components.
- Have limited frequency range

3.7.1.4 Velocity transducers

Today, a vast majority of machinery vibration information is recorded and quantified in terms of velocity. Most vibration measurements in the process industries are analyzed in terms of inches per second (ips) in the United States, or mm/sec on the SI systems. Velocity readings are generally recommended for measurements in the 100 to 30,000 CPM (1.7 to 500 Hz) frequency band.

The main types of velocity tranducers :

3.7.1.4.1 Piezo-Velocity transducers

For many permanent sensor installations in paper mills, steel, and power generation facilities, a PVT sensor is the best investment. The PVT is essentially a piezoelectric accelerometer with an on-board velocity converter. The transducer employs a piezoceramic sensing element and dense seismic mass to produce a charge output proportional to acceleration. The high impedance charge signal is converted within the sensors to a low impedance voltage output and integrated to velocity [4]. Section views of compression and shear mode PVTs are shown in Figure 3.

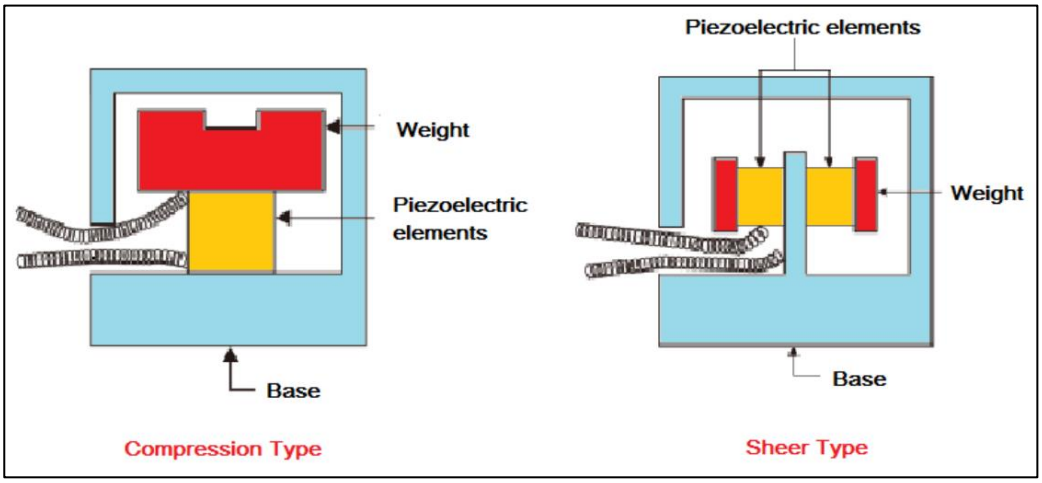


Figure 3-13 Two types of piezoelectric

3.7.1.4.2 Velocity Pickup transducers

Velocity pickup transducer consists of coils, wire, and magnet and was arranged so that if the housing is moved, the magnet tends to remain stationary due to its inertia (see Figure 3.5). The relative motion between the magnetic field and the coil induces a current that is proportional to the velocity of motion and the unit produces a signal directly proportional to vibration velocity.

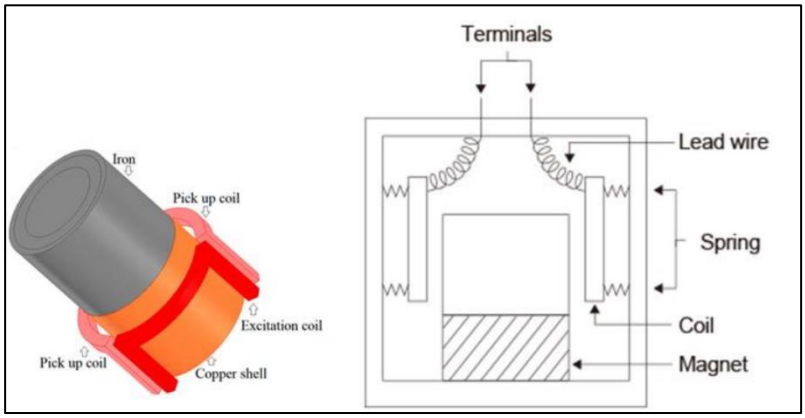


Figure 3-14 Velocity sensor: a) Geometry of two pickup coils, b) Finite element modeling

3.7.1.4.3 Features

- Simple to install
- Good response in middle range frequencies
- Stand high temperature
- Do not require external power
- Lowest cost

3.7.1.4.4 Limitations

- Low resonant frequency and phase shift
- Cross noise
- Big and heavy
- Require electronic integration for displacement

3.7.1.5 Accelerometers transducers

Piezoelectric accelerometer is a self-generating device. The idea is that when a piezoelectric material is subjected to a mechanical stress (shear, compression, or bending), an electric signal generates across its faces and proportional to the stress (see Figure 3.6).

Its frequency range is from below 1 to 10000 Hz.

Certain natural and manufactured materials like quartz, tourmaline, lithium sulfate, and Rochelle salt generate electrical charge when subjected to a deformation or mechanical stress.

The electrical charge disappears when the mechanical loading is removed.

Such materials are called piezoelectric materials and the transducers, which take advantage of the piezoelectric effect, are known as piezoelectric transducers.

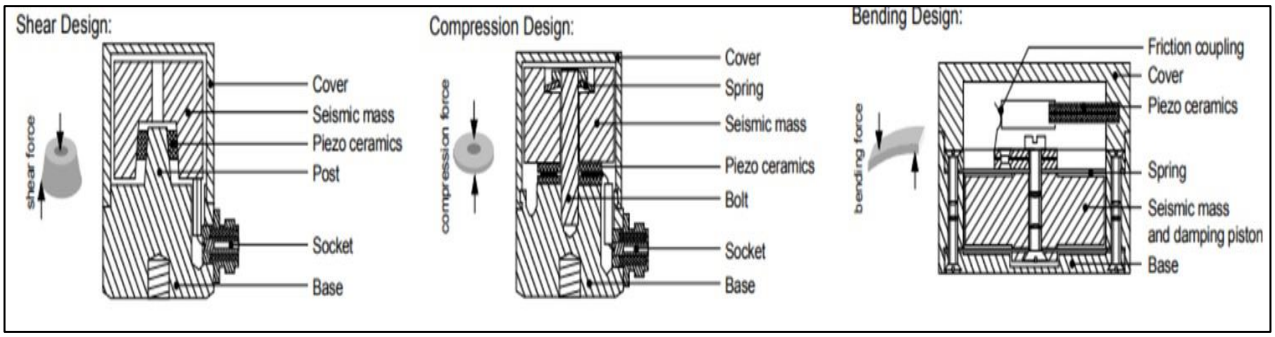


Figure 3-15 Piezoelectric accelerometers

3.7.1.5.1 Features

- Use in a wide frequency range (0.3-40kHz)
- Excellent linearity over a wide dynamic range
- Possibility to integrate the signal to give information in speed and travel mode
- Excellent accuracy for a wide range of environmental conditions (-50 to 700°C)
- Excellent reliability over time (no moving parts)
- Small footprint and high mass sensitivity ratio

3.7.1.5.2 Limitations

- Sensitive to mounting technique and surface condition
- Cannot measure relative vibration or shaft position
- Low dynamic signal response below 10 Hz;

- Sensitive to noise, motion and electrical interference

3.8 Types of Monitoring System

3.8.1.1 Intermittent Monitoring System "off-line "

Intermittent monitoring system also called an off-line condition monitoring system is based on measuring vibration at selected time intervals in the field. Then, the analysis will be performed either in the field or later after data collection. Intermittent monitoring provides information at an early stage about incipient failure and usually is used where very early warning of faults is required, advanced diagnosis is required, measurement must be made at many locations on a machine, and machines are complex. [4]

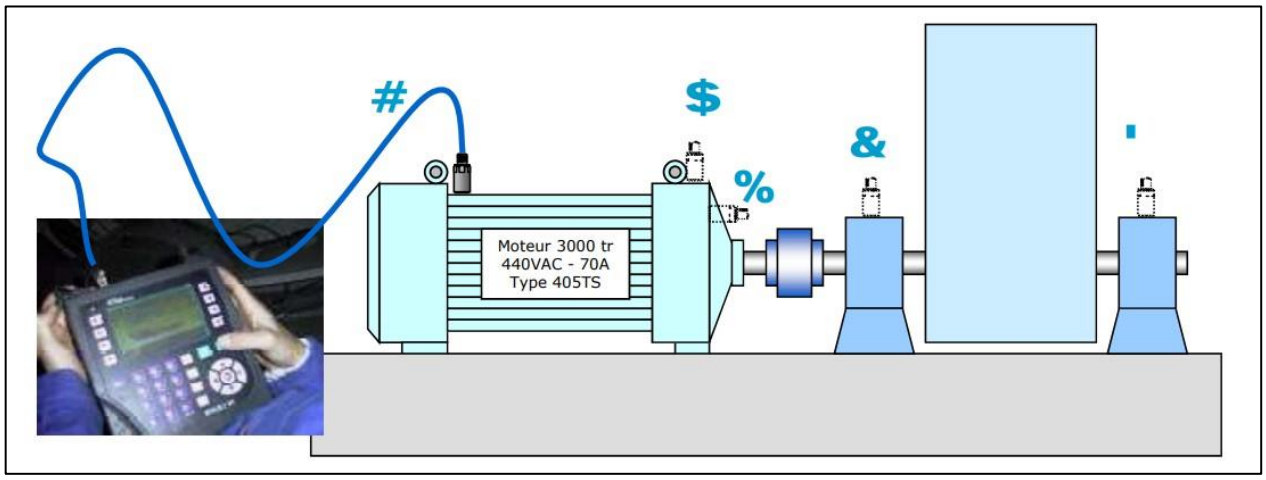


Figure 3-16 Off-line monitoring

3.8.1.2 Permanent monitoring system "on-line "

Permanent monitoring system also called an on-line condition monitoring system is based on measuring vibration continuously at selected points of the machine and comparing the measurements with the acceptable levels of vibration. In the permanent monitoring system, transducers are mounted permanently at each selected measurement point.

Usually, permanent monitoring system used in critical applications where:

- No personnel are available to perform measurements (off shore, remote pumping stations, etc.).
- It is necessary to stop the machine before a breakdown occurs in order to avoid a catastrophic accident.

- An instantaneous fault may occur that requires machine shutdown.
- The environment (explosive, toxic, or high-temperature) does not permit the human involvement
- It used also when we need to protect the machine at real time ‘’ the case of expensive machine ‘’

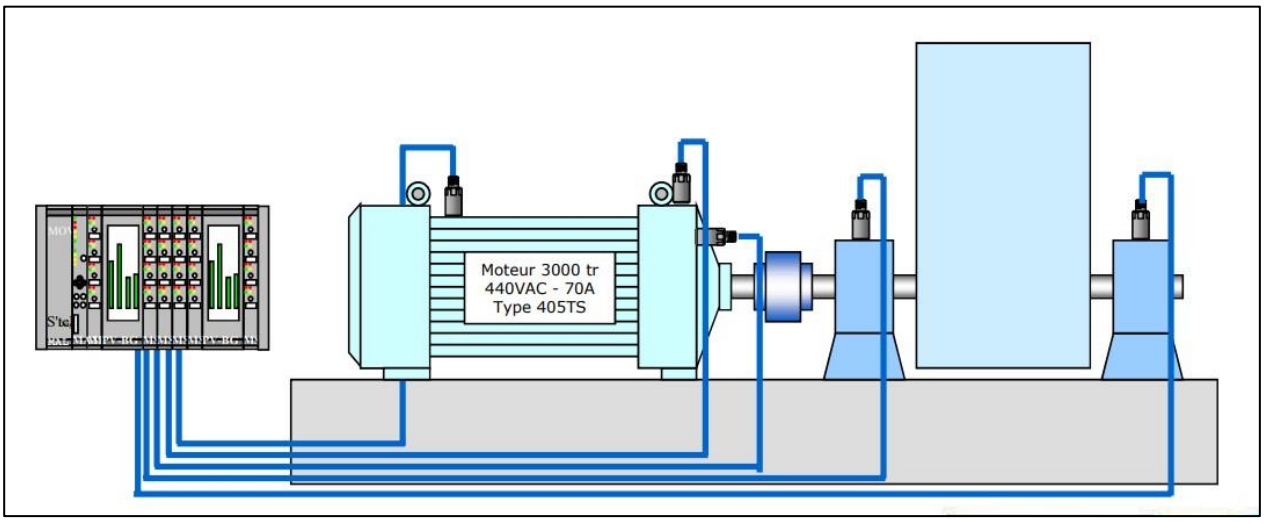


Figure 3-17 On-line monitoring

3.9 Data acquisition

Vibration data collection is one of the most important steps in analyzing issues caused by machinery vibration. If done correctly, your analysis, recommendations and reporting become much more accurate.

3.9.1.1 Automated Method

In this method, accelerometers are permanently mounted on machines and terminated into data acquisition Units, which collect and process data at designated intervals (every minute, hourly, daily, weekly, etc.), depend on the criticality of the machine. As shown in Figure 6.1, this method has a simplified layout with less personnel involvement in the day-today operations of the process. Data collected can be made available instantly online for all stakeholders to view.

3.9.1.2 Manual Method

This entails the use of trained personnel to download routes manually from software on a computer onto a data collector. The data collector is carried around the plant (from one machine to the other)

and used to collect data from each designated location on a machine. Data is collected on the average interval of once per month, or quarter, while under normal operating condition. After data has been collected, the device is connected to a computer and the routes uploaded back into the software for analysis. As depicted in Figure 6.2, this method relies on a lot of manual involvement by trained personnel to ensure the process is efficient. Data collected is commonly exported and sent by email to other stakeholders who may not have access to the local computer where the software is installed.

3.9.1.3 Sampling rate & phenomenon of aliasing

Sampling involves capturing the amplitude of a wave at specific moments, forming a curve from these points. This process converts the continuous analog wave into discrete digital data points. To accurately reconstruct the original analog wave, the sampled data points must mirror it closely. The Nyquist sampling theorem provides guidance here, stating that:

'If we are not tolose any information contained in a sampled signal, we must sample at a frequency rate of at least twice the highest frequency component of interest.'

Figure 6.4 (left) displays examples for low and high sampling rate. It was observed that when the sampling rate is too low (under sampling rate), another wave can be generated with a different frequency rather than the original wave frequency. The sampling rate needs to increase to make a correct representation for the original wave as shown in Figure 6.4 (right). The phenomenon of a lower frequency wave due to under sampling is called aliasing. All data collectors/analyzers have automatically selected built-in sampling rates and fitted with an antialiasing filter. The antialiasing filter is a low pass electronic filter which allows low frequencies to pass and prevents higher ones. The filter removes all vibrations in the analog signal that have frequencies greater than half the sampling rate. It is automatically tuned to the proper values as the sampling frequency is changed (this occurs when the frequency range of the analyzer is changed by the user). It is very important to note that filtering has to occur before digitization of the analog commences.

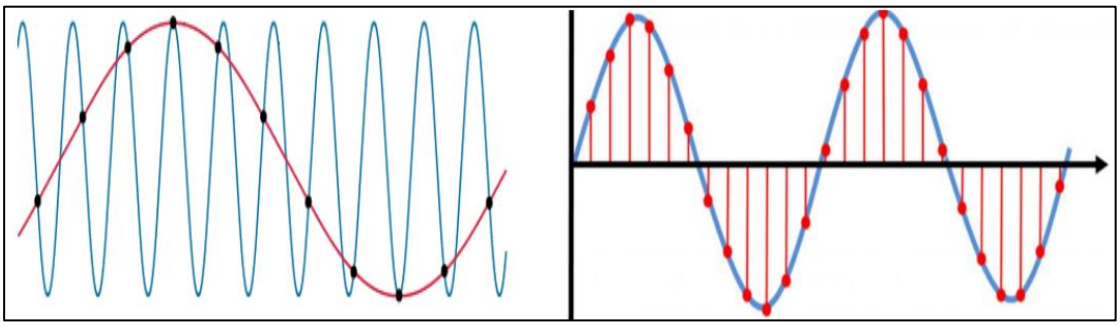


Figure 3-18 Example of low sampling rate (left), high sampling rate

3.9.1.4 Analog anti-aliasing filtering of the signal 'before its sampling'

Anti-aliasing filters play a crucial role in vibration analysis by preventing aliasing artifacts. In vibration analysis, signals from sensors are sampled to capture the vibrations of a system. However, if the sampling rate is too low, it can lead to aliasing, where high-frequency vibrations are misrepresented as lower frequencies, distorting the analysis results.

An anti-aliasing filter is used to remove or attenuate high-frequency components from the signal before sampling, ensuring that only the relevant frequency components are captured accurately. By filtering out unwanted high-frequency content, the filter helps prevent aliasing and ensures that the sampled data accurately represents the original vibration signal. This is particularly important in applications where precise frequency analysis is essential for understanding the behavior of mechanical systems and detecting potential faults or anomalies.

3.10 Signal processing

Since the captured data from the transducer are continuous analog signals, some methods of signal processing have to be performed for further analysis such as windowing, averaging, filtering, and else[4].

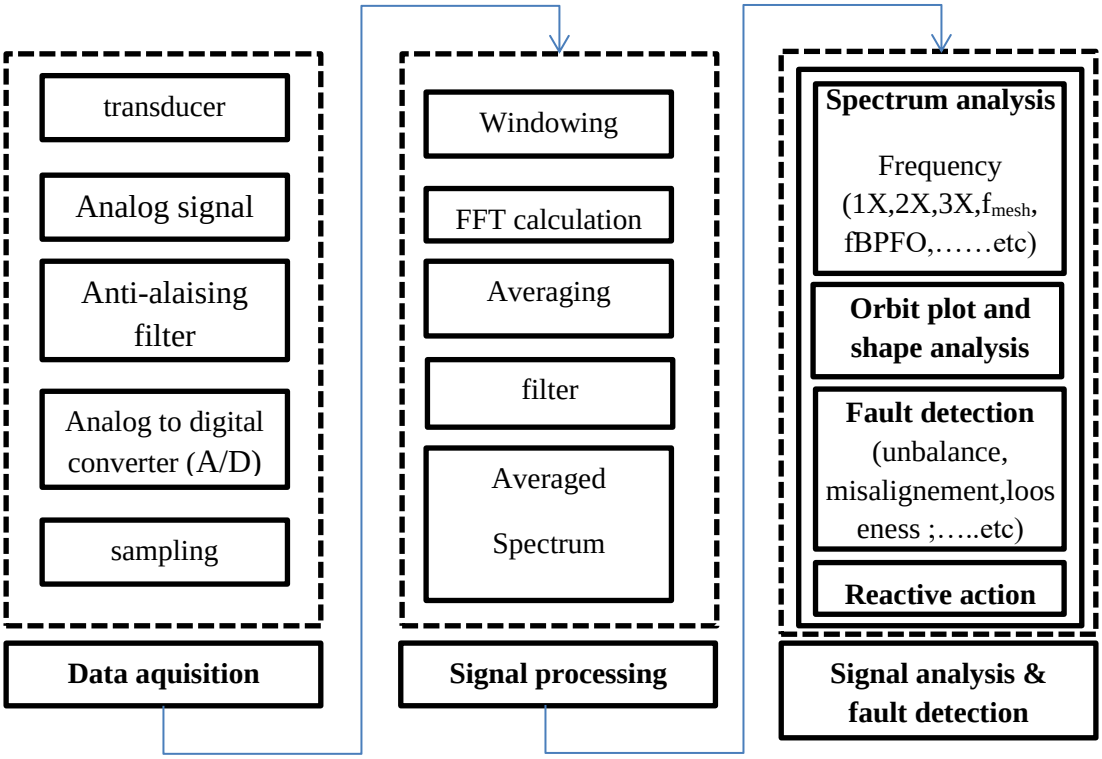


Figure 3-19 Signal processing steps

3.10.1.1 Windowing

In signal processing, a window function is a mathematical function that is zero-valued outside of some chosen interval, normally symmetric around the middle of the interval, usually near a maximum in the middle, and usually tapering away from the middle as shown in Figure 7.1.

In actual practice, the segment of data within the window is first isolated, and then only that data is multiplied by the window function values.

The reasons for examining segments of a longer function include detection of transient events and time-averaging of frequency spectra.

The duration of the segments is determined by requirements like time and frequency resolution. But that method also changes the frequency content of the signal by an effect called spectral leakage.

3.10.1.2 Types of window functions

There are different types of window functions:

- ✓ Rectangular Window
- ✓ Hanning window
- ✓ Hamming window
- ✓ Blackman-Harris Window
- ✓ Flat Top Window

3.10.1.2.1 Rectangular Window

a rectangular window is a mathematical function often used for the purpose of signal processing. It is a simple window function where the values within a specified range are set to 1, and outside that range are set to 0. This creates a rectangular shape when plotted, hence the name. These rectangular windows are commonly used in Fourier analysis and in filtering operations on digital signals.

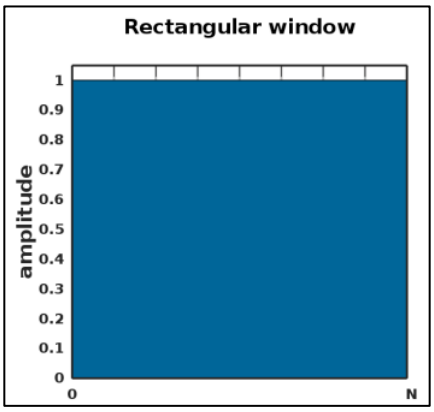


Figure 3-20 Rectangular window functions.

3.10.1.2.2 Hanning Window

The Hanning window, also known as the Hann window or raised cosine window, is another type of window function commonly used in signal processing. It is designed to taper the ends of a signal to zero, reducing spectral leakage when performing Fourier analysis or other operations.

The Hanning window is defined mathematically as a weighted function that smoothly transitions from 0 at the edges to 1 in the center, resembling a raised cosine shape. It is given by the formula:

$$w(n)=0.5(1-\cos(\frac{2\pi n}{N-1}))$$

where:

- ✓ w(n) is the value of the window at sample n.
- ✓ N is the total number of samples in the window.
- ✓ n ranges from 0 to N−1.

The Hanning window is widely used in various signal processing applications, such as spectral analysis, filter design, and windowing of time-domain signals, due to its good trade-off between main lobe width and side lobe attenuation.

3.10.1.2.3 Hamming Window

the Hamming window is another type of window function used in signal processing, similar to the Hanning window. Like the Hanning window, it is designed to taper the ends of a signal to zero, reducing spectral leakage when performing Fourier analysis or other operations.

The Hamming window is defined mathematically as:

$$w(n)=0.54-0.46\cos\left(\frac{2\pi n}{N-1}\right)$$

where:

- ✓ w(n) is the value of the window at sample n.
- ✓ N is the total number of samples in the window.
- ✓ n ranges from 0 to N−1.

Compared to the Hanning window, the Hamming window has a slightly narrower main lobe and wider side lobes, which can be beneficial in certain applications. The coefficients used in the Hamming window are chosen to minimize the amplitude of the first side lobe, resulting in better attenuation of nearby frequencies.

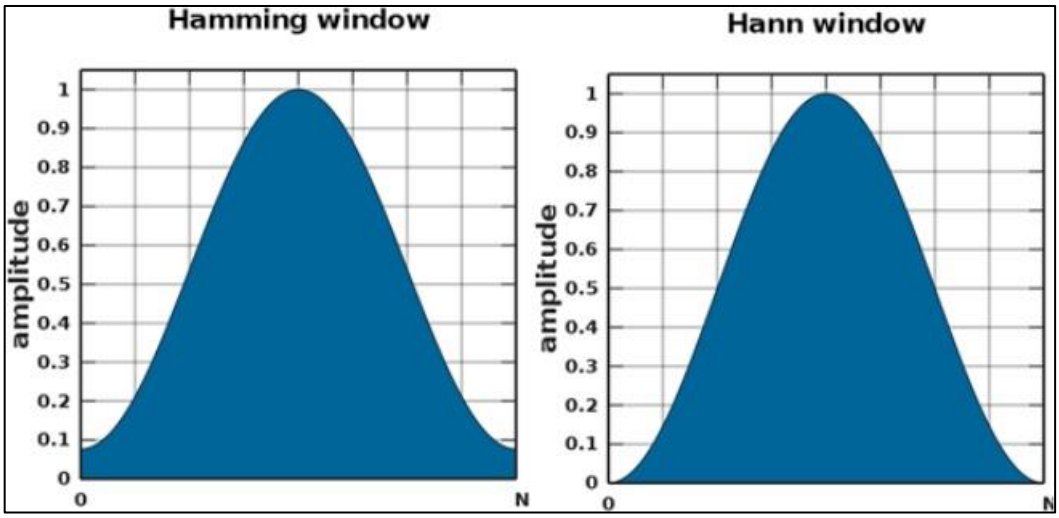


Figure 3-21 Hamming and hann window functions.

3.10.1.2.4 Blackman-Harris Window

The Blackman-Harris window is a family of window functions that includes several variations, each with different parameter values. These windows are designed to minimize side lobes and

spectral leakage in signal processing applications, particularly in cases where high dynamic range and low passband ripple are desired.

The general formula for the Blackman-Harris window is:

$$w(n)=a_0-a_1\cos(\frac{2\pi n}{N-1})+a_2\cos(\frac{4\pi n}{N-1})-a_3\cos(\frac{6\pi n}{N-1})$$

where:

- ✓ w(n) is the value of the window at sample n.
- ✓ N is the total number of samples in the window.
- ✓ a_0,a_1,a_2, and a_3 are coefficients that depend on the specific variation of the Blackman-Harris window.

The most commonly used variation of the Blackman-Harris window is the 4-term window, which has the following coefficients: $a_0=0.35875$,$a_1=0.48829$,$a_2=0.14128$,$a_3=0.01168$

This variation provides a good balance between main lobe width and side lobe attenuation.

The Blackman-Harris window family also includes other variations such as the 3-term and 7-term windows, each with different sets of coefficients optimized for specific applications. These windows are widely used in various signal processing tasks, including spectral analysis, filter design, and windowing of time-domain signals, where minimizing spectral leakage and side lobes is important.

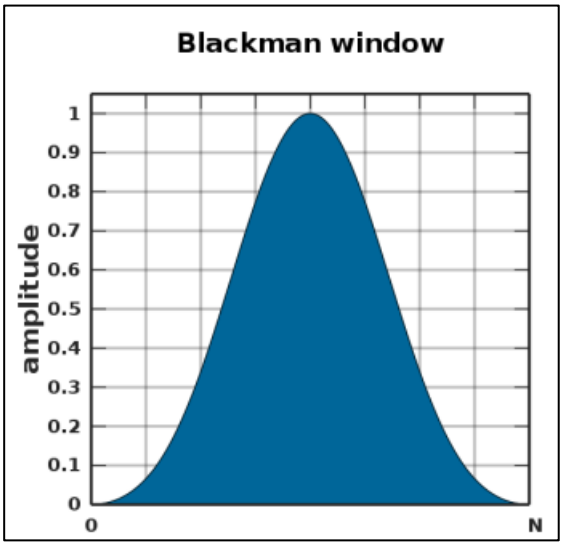


Figure 3-22 Blackman-Harris window functions.

3.10.1.2.5 Flat Top Window

The Flat Top window is a specific type of window function used in signal processing applications, particularly in cases where accurate amplitude measurements of sinusoidal components are necessary. It is designed to flatten the top of the window, hence its name, to make amplitude measurements more accurate by minimizing the effects of spectral leakage.

The Flat Top window is defined mathematically as:

$$w(n) = \sum_{k=1}^{N-1} a_k \cdot \cos\left(\frac{2\pi nk}{N-1}\right)$$

where:

- ✓ w(n) is the value of the window at sample n.
- ✓ N is the total number of samples in the window.
- ✓ a_k are the window coefficients.

The Flat Top window typically uses a set of specific coefficients to achieve its desired properties. The most commonly used set of coefficients for the Flat Top window is:a_0=1, a_1=1.93, a_2=1.29, a_3=0.388, a_4 =0.032

This set of coefficients results in a window function that minimizes the amplitude error when measuring sinusoidal components in a signal. The Flat Top window is widely used in spectrum analyzers and other measurement equipment where accurate amplitude measurements are critical.

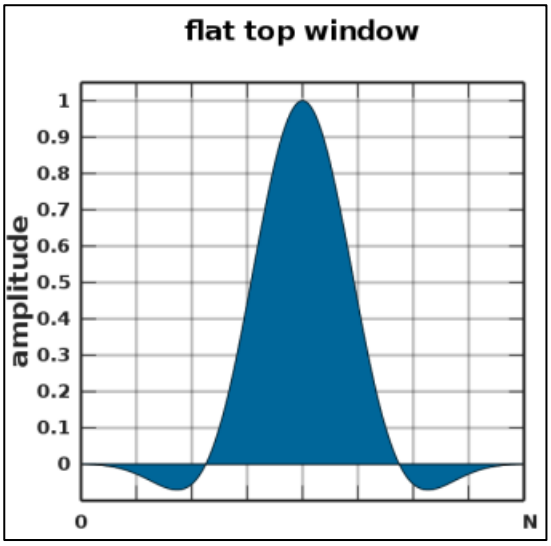


Figure 3-23 Flat top window function.

3.10.1.3 Averaging

Signal averaging is a technique used in signal processing to improve the quality of a signal by reducing random noise. It involves collecting multiple measurements of the same signal and averaging them together to obtain a single, smoother representation.

3.10.1.4 Linear averaging

Linear averaging in signal processing refers to a method of averaging multiple samples of spectrums to obtain a averaged spectrum, smoothed representation of the signal. It involves taking the arithmetic mean of the individual samples.

The process of linear averaging can be described as follows:

- Collect Samples: Multiple spectrums of signal windows are acquired over a certain period of time or number of repetitions
- Summation: The values of the spectrums are added together.
- Normalization: The sum is divided by the total number of samples to compute the arithmetic mean, or average.

Mathematically, linear averaging can be represented as:

$$Average = \frac{1}{N}\sum_{i=1}^{N} x_i$$

where:

- Average is the computed average of the samples,
- N is the total number of samples,
- x_i are the frequencies within the same spectral line.

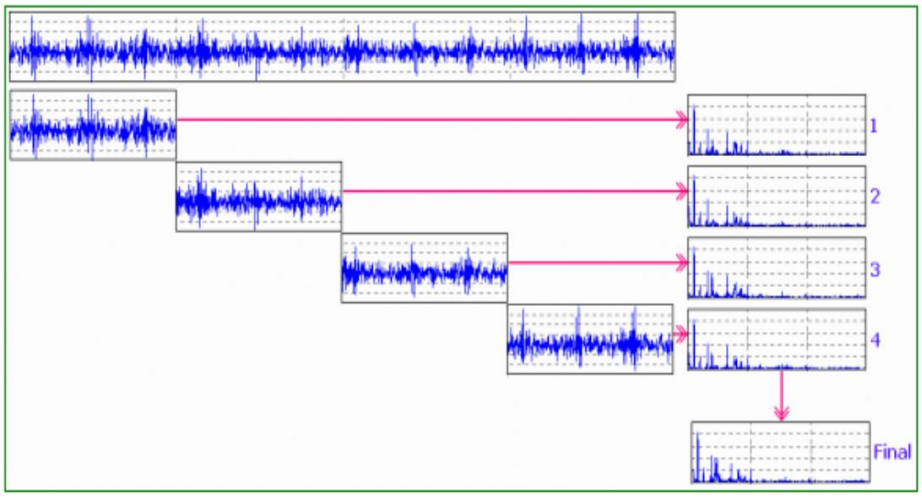


Figure 3-24 Linear averaging

3.10.1.5 Overlap averaging

This method is particularly useful when dealing with long signals or signals with varying characteristics over time. Instead of averaging non-overlapping segments, as in traditional block averaging, overlap averaging allows adjacent segments to overlap, providing smoother transitions between consecutive averages.

Here's how overlap averaging typically works:

- **Segmentation**: The signal is divided into overlapping segments of equal length. The segments can overlap by a certain percentage, often referred to as the overlap factor.
- **Averaging**: Successive spectrum are averaged together.
- **Overlap Factor**: The overlap factor determines how much overlap there is between adjacent segments. For example, an overlap factor of 50% means that each segment overlaps the previous one by 50% of its length.

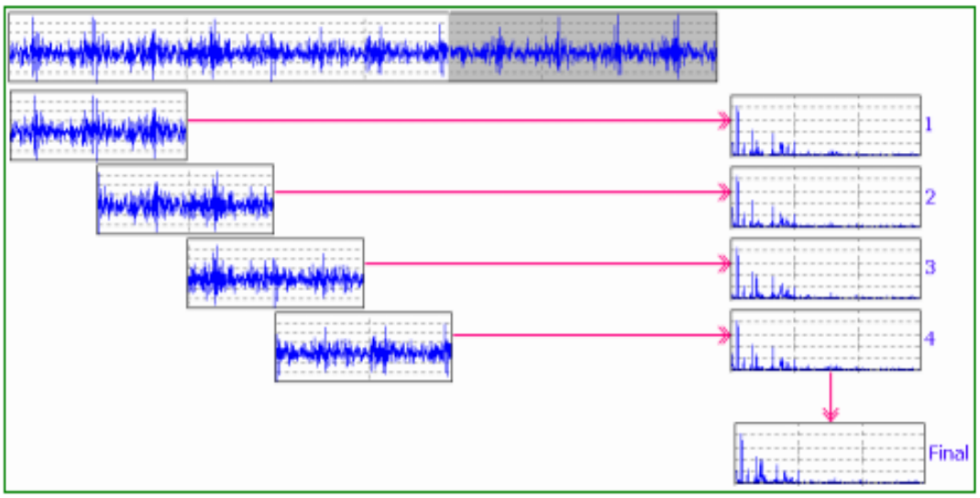


Figure 3-25 Overlap averaging

3.10.1.6 Peak Hold Averaging

Peak hold develops an envelope of the highest spectral line amplitude measured for any average. This technique is used for viewing transients such as impact and run up / coast down tests.

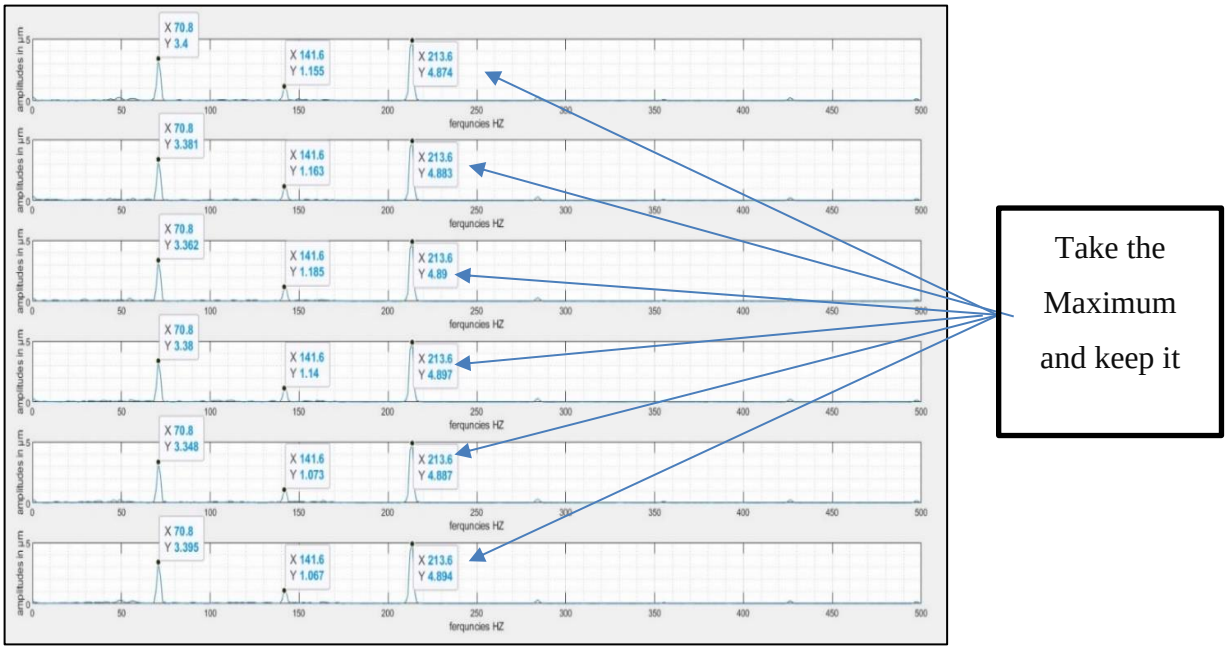


Figure 3-26 Peak-hold averaging

3.10.1.7 filtering

In signal processing and vibration analysis, filters play a crucial role in extracting relevant information from signals, removing noise, and identifying specific frequency components. Filters are used to modify the frequency content of a signal by allowing certain frequencies to pass through while attenuating others. Here are some common types of filters used in signal processing and vibration analysis:

There are 4 types of filters: [10]

• Low pass: Passes below a limit frequency

• Bandpass: Passes in a frequency band

• Band-Stop: Passes outside a frequency band

• High pass: Passes over a limit frequency

3.11Types of faults in rotating machines

In this section, we examine different faults in rotating machines. These generally relate to a rotating shaft, bearing, gearbox, rotor, stator, etc[15].

3.11.1.1 Shaft unbalance

Definition: Rotation of shaft is more to one side. It is an unequal distribution of mass t

There are three types:

a- Static unbalance the principle inertia axis & the geometric centerline are parallel
b- Couple unbalance the principle inertia axis & the geometric centerline are intersect in the center
c- Dynamic unbalance the principle inertia axis & the geometric centerline are not touch or coincide

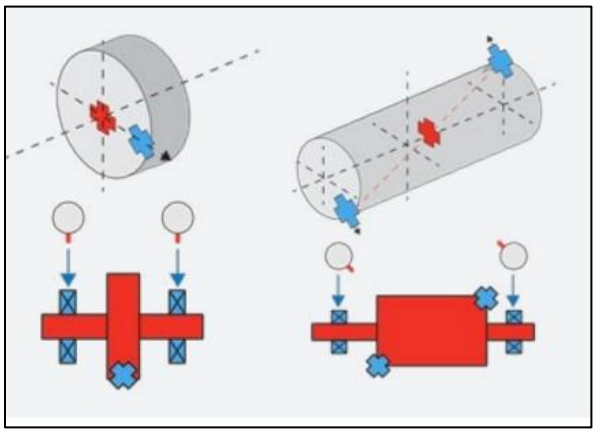


Figure 3-27 Static and couple unbalance

Cause: Unbalance is the unequal distribution of mass within a rotating system (dust on fan, erosion of blade, porous material). The geometric centerline of rotation does not coincide with its mass centerline.

Effect: Excitation forces rotating at the shaft speed is generated mainly in radial direction. Dynamic balancing (adding weights) to shaft is done to mitigate effect.

Detection: Fault is detected at a frequency of 1* RPM in the form of a 180°phase shift across the coupling. (Note: RPM = rotation per minute of shaft).

3.11.1.2 Shaft misalignment

Definition: Coupling between two rotors with their supports are not aligned. They can be parallel misaligned or angular misaligned. Cause: Assembly issue, unlevelled foundation, the coupling loosens through use over time.

Effect: The rotating shaft can bend after a bearing failure. Flexible coupling is used to mitigate the effects.

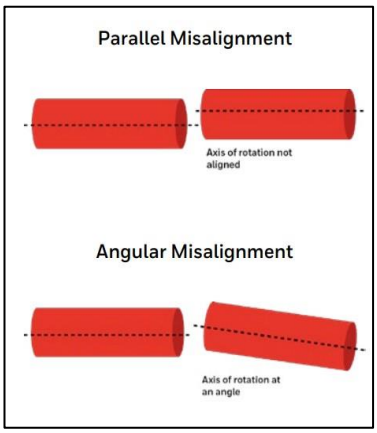
Detection:

Angular misalignment

- ✓ Strong axial vibration at 1x RPM possibly with 2x and 3x harmonics (i.e. vibration at 2x and 3x RPM).
- ✓ The 2x RPM harmonic in the axial direction can reach a value equal to or even higher than 1x.
- ✓ Vibration in the radial direction, probably of smaller amplitude than in the axial direction, in 1x, 2x and 3x.
- ✓ The axial phase measurements on both sides of the coupling are 180° out of phase.

Parallel or offset misalignment

- ✓ Strong radial vibration in 1x RPM with 2x and 3x harmonics.
- ✓ The 2x RPM harmonic in the radial direction can reach a value equal to or even greater than 1x.
- ✓ The radial phase measurements on both sides of the coupling are 180° out of phase.



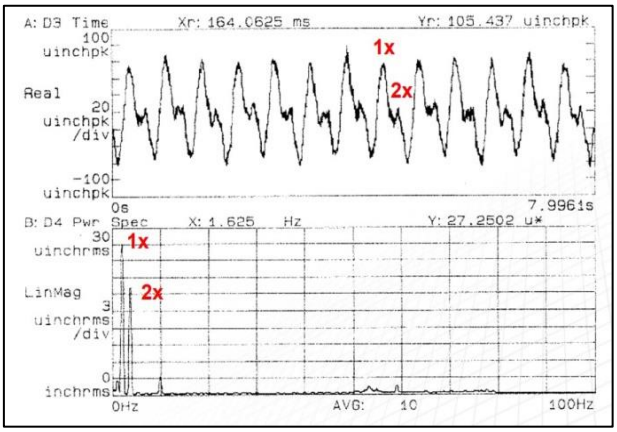


Figure 3-28 Types of misalignment example of misalignment waveform& spectrum

3.11.1.3 Bent shaft

Definition: A rotor is considered bent (permanently bowed) when it loses its symmetry with respect to its rotating axis.

Cause: Thermal expansion and higher axial load.

Effect: This fault will show signs of misalignment and unbalance and can change with temperature.

Detection: It can cause a 1× RPM, 2× RPM component in the axial and radial direction. However, unlike unbalance, a significant axial vibration will be measured. Phase shift across the coupling at 180° in axial direction.

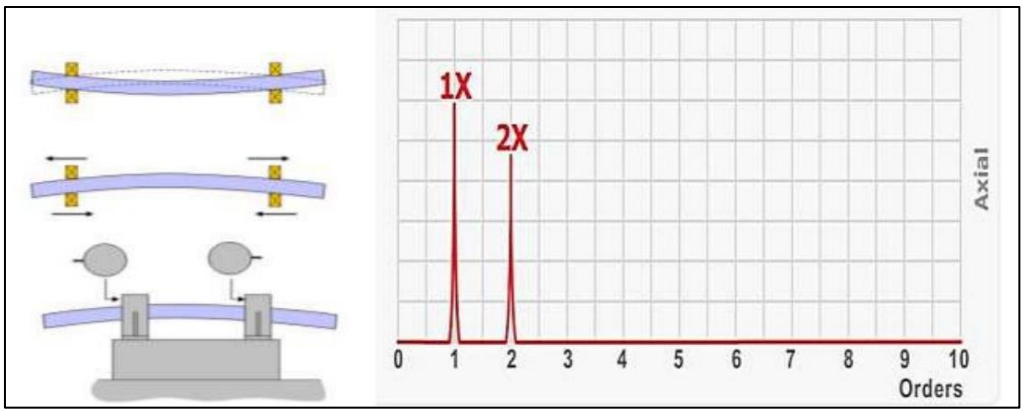


Figure 3-29 Example of bent shaft and its spectrum

3.11.1.4 Looseness

Definition: Not enough tightening between different mechanical elements. It can be categorized into two types: looseness of rotating elements (rolling element bearings, sleeve bearings, couplings, rotors, etc.); and structural looseness (benches, casters, anchor bolts, etc.).

Cause: Assembly issues, clearance increase due to wear.

Effect: Can lead to unbalance, misalignment, bent shaft.

Detection:

Rotating element looseness

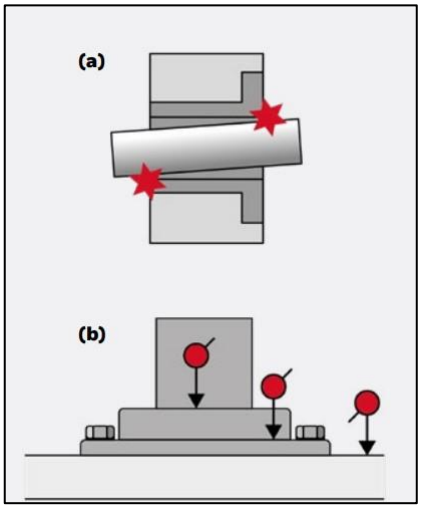


Figure 3-30 Looseness (a) Rotating element (b) Structural

- ✓ Presence of frequency with harmonics (1x, 2x, 3x, etc.), subharmonics (0.5x) and half harmonics (1.5x, 2.5x, 3.5x, etc.).
- ✓ More in radial directions than axial.

Structural looseness

- ✓ Presence of frequency with harmonics (1x, 2x, 3x) in radial direction. Amplitude of 2x,3x and higher than 1x

3.11.1.5 Oil whirl and oil whip

Definition: It occurs in fluid film bearing when lightly loaded. It is like a shaft surfing over fluid film.

Cause: At lower loads, there is a mismatch in velocity of oil adjacent to the shaft and the bearing surface. Additionally, misalignment of foundation, thermal effect.

Effect: It can be destructive. It can be eliminated by design or non-cylindrical bearing or tilting pad bearing.

Detection: Vibration at subharmonics (0.5x, 0.3x)

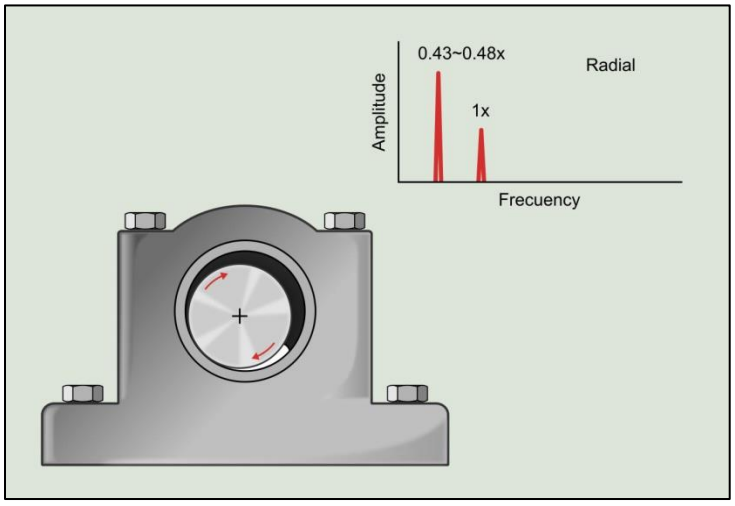


Figure 3-31 Oil whirl and whip

3.11.1.6 Bearing fault

Definition: Defects on the bearing components (fundamental train frequency (FTF), ball spin frequency (BSF), ball pass frequency outer race (BPFO), and ball pass frequency inner race (BPFI). Defects include cracks, wear, pitting etc.

Cause: Degraded lubricant, external environment, fatigue, variable frequency drive currents.

Effect: Misalignment leading to higher vibration and complete coupling failure leading to secondary damage.

Detection: Presence of frequency at characteristic fault frequencies related to bearing components with sidebands. Sidebands are frequencies which would be present around the characteristic fault frequencies.

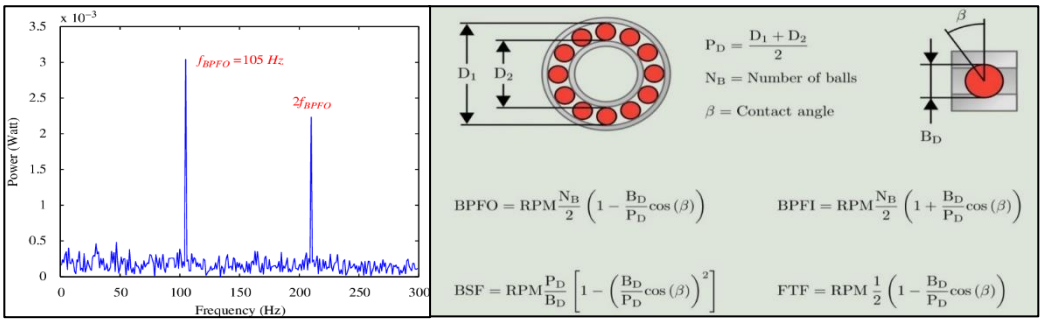


Figure 3-32 Spectrum and Bearing components frequencies

3.11.1.7 Gear fault

Definition: Defects on the gear teeth. Defects include cracks, pitting, missing teeth.

Cause: Degraded lubricant, external environment, fatigue, damaged bearing.

Effect: Misalignment leading to higher vibration, torque imbalance.

Detection: Increase in 2xGMF at initial state followed by harmonics. Note: GMF = gear meshing frequency, i.e., frequency at which gear teeth roll. (GMF= number of teeth x rotating shaft speed).



Figure 3-33 Gear defects

3.11.1.8 Bladed machines faults

Definition: Defect in blades or vanes found in fans, pumps, compressors and turbines. Defects include cracks, pitting, missing parts.

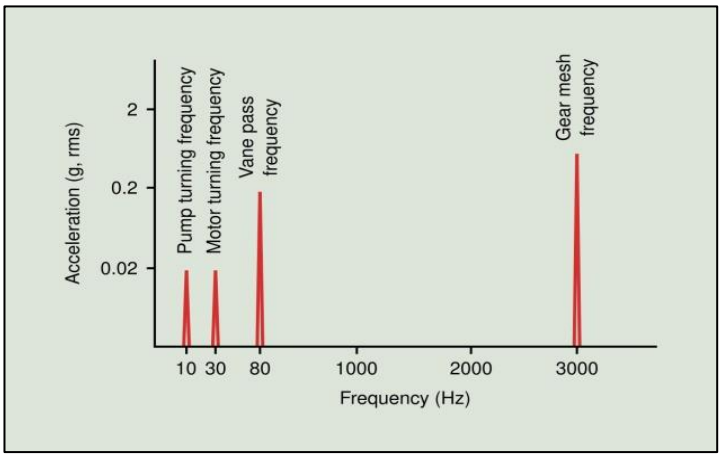


Figure 3-34 Gear mesh frequency

Cause: Cavitation, fatigue.

Effect: Catastrophic (sometimes) and can lead to secondary damage on other connected components.

Detection: Increase in amplitude at blade pass frequency (number of blades x rotating shaft speed).



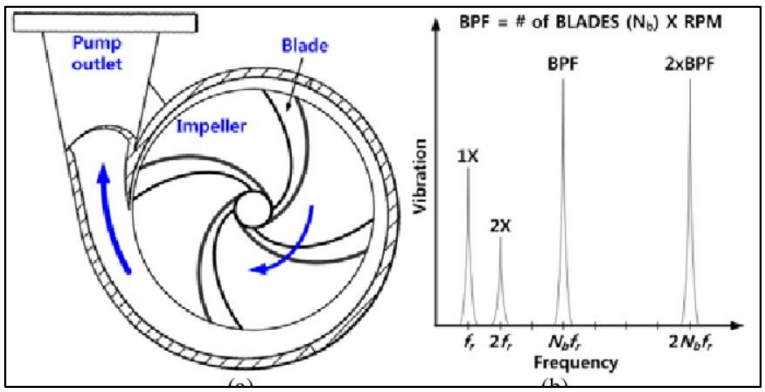


Figure 3-35 (Left) :Centrifugal pump blade erosion, (Right):Drawing & spectrum

3.11.1.9 Eccentricity

Definition: Offset between the axis of rotation and the axis of symmetry. Eccentricity can take place in different types of mechanical elements, such as pulleys, gears and in any relative positioning between two concentric pieces -- for example, the rotor and stator of an electric motor.

Cause: Uneven surface wear or manufacturing issue or assembly issue.

Effect: Torque unbalance.

Detection: Frequency of elements involved (e.g., speed of motor and pulley).

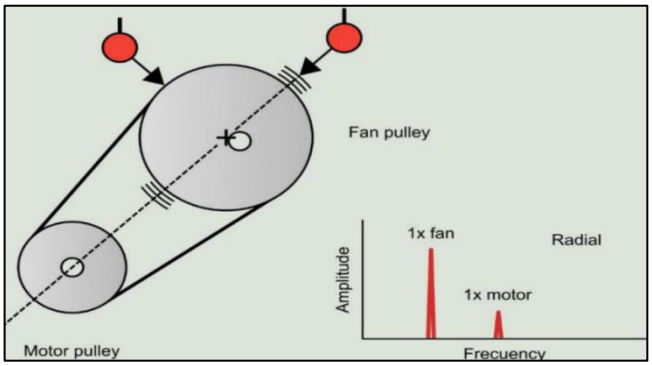


Figure 3-36 Eccentric rotor

3.11.1.10 Cracked shaft

Definition: Surface of shaft has transverse crack which can open and close during the operation.

Cause: Manufacturing defect, wear due to environment (inside and outside).

Effect: Can be catastrophic.

Detection: Open crack at a 1× RPM, 2× RPM. Breathing crack at 1× RPM, 2× RPM and 3xRPM (higher).



Figure 3-37 Cracked shaft due to corrosion

3.12 Conclusion

This chapter is a combination of principles of vibrations and signal processing, followed by common faults and how to analyze the waveform and spectrums.

4 th Chapter Signal processing through MATLAB

4.1 Introduction

In this chapter, we delve into the crucial area of data analysis and interpretation. Our goal is to harness the power of MATLAB software for vibration analysis, enabling us to process and make sense of the data we have collected. Through sophisticated techniques and equipment, we aim to reveal ideas hidden in vibration analysis and signal processing.

Firstly, we need to collect data from radial vibration probes installed in the journal bearing of a centrifugal compressor. In our study, it's essential to gather the actual values from the sensors without alterations. Subsequently, we will utilize MATLAB for processing this data. To achieve this, we must use a VT 80 from Brüel & Kjær, connected to a BENTLY NEVADA 3500 rack Figure 4-1.



Figure 4-1 Rack room

4.2 VIBROTEST 80 (VT 80)

The VT 80 (Figure 4-2) is a portable and flexible vibration measuring and balancing instrument. It can be used for a multitude of measuring tasks and supports up to four input channels for vibration signals, to which all standard types of vibration sensors can be connected. It is thus ideally suited for early fault detection and diagnosis of imminent faults in bearings, shafts, transmissions, couplings and housings of auxiliary units, as well as production-critical machines.



Figure 4-2 VIBROTEST 80 unboxing

Also, we can use the VT 80 as portable data acquisition and storage device with up to four input channels for vibration. In conjunction with visual checks, the VT 80 enables detailed analysis of machine states even in extreme industrial environments. The relevant data are logged, displayed and stored.

To connect or read collected data, Brüel & Kjær offers an application called Report & Route Manager software – The Report & Route Manager software simplifies organizing and evaluating the collected measurement data. From among the plant, the user can select the specific machine that needs immediate maintenance.

The software then allows him to identify a potential fault and what caused it as early as possible. Data collection routes are defined and uploaded to the instrument. Measured data is downloaded and stored in the database for further analysis[16].

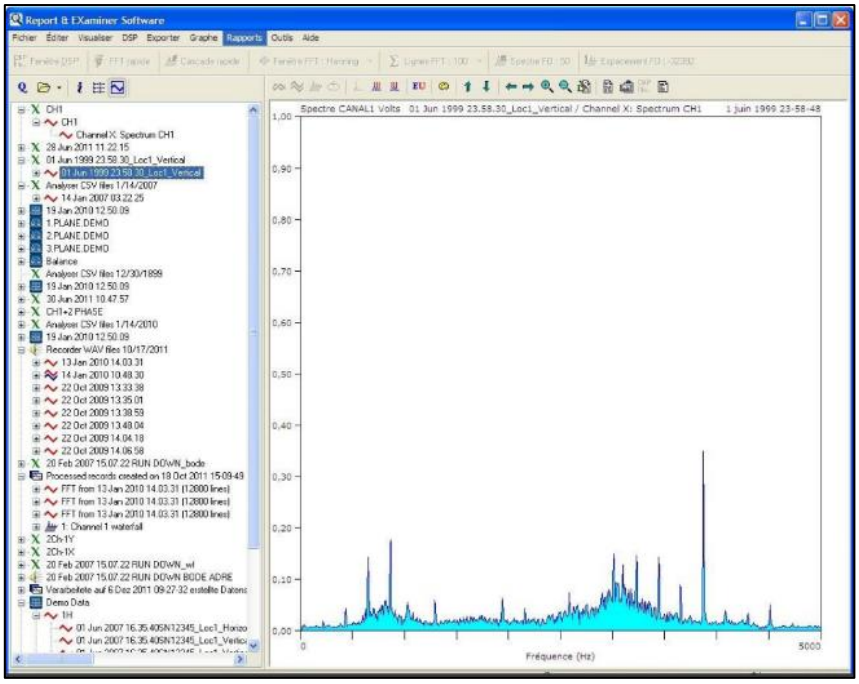


Figure 4-3 Report & Route Manager software interface

4.2.1.1 Descriptions of VT 80

In the following we give an overview of the hardware for the VT 80.

The connection plate of the VT 80 contains four connections (sockets) for connecting sensors, power supply modules and USB devices

[1] Input keys

[2] Indicator lights (3x L

[3] Display

[4] Function keys (1 to 4), Further function keys accessible with the shift function [0↑]

[5] Cursor keys (left, right, up, down)

[6] On/Off button

[7] Alphanumeric keypad

[8] Shift key to display lower softkeys



Figure 4-4 VT80 overview

In addition to the internal memory, the VT 80 has a storage card slot for inserting an SD storage card with up to 16 GB storage capacity.

4.3 Bently Nevada 3500

The **3500 system** is capable of detecting and preventing both missed-trips and false-trips in rotating machinery. It provides automatic protection value by stopping monitored machines to prevent expensive damage when needed.

The **3500 system** also protects our machines and processes against false-trips that could bring our operation down for no reason, resulting in a costly outage or loss of production.

When connected with a VT 80, it also provides a possibility to collect information for use in a proactive maintenance program.

The **3500 system** incorporates the industry's most extensive selection of machinery measurement parameters combined with software configuration for virtually all machinery monitoring scenarios.



Figure 4-5 Bently Nevada 3500

4.4 Data collecting

4.4.1.1 Operating mode

To connect a VT 80 to a Bently Nevada 3500 rack for data collection in the time domain, you typically need appropriate interface cables and connectors compatible with both systems. Here's a general guideline on how you can achieve this connection:

- ✓ **Identify compatible interface cables**: Look for cables that can connect the VT 80 to the Bently Nevada 3500 rack.
- ✓ **Connection:** connect the VT 80 to the Bently Nevada 3500 rack in the connection 102X & 102Y.

- ✓ **Configure the connection:** Once the physical connection is established, you may need to configure the communication settings on the VT 80 to ensure proper data transmission. This may involve setting up communication configuration, Fmax, and other parameters as the date, the user and others settings.
- ✓ **Test the connection:** After configuring the connection, perform a test to ensure that data can be successfully transmitted from the Bently Nevada 3500 rack to the VT 80.
- ✓ **Collect data:** Once the connection is established and tested, you can start collecting data from the radial vibration probes "102X & 102Y" installed in the centrifugal compressor. The VT 80 will acquire the vibration data, which can then be processed and analyzed using MATLAB.



Figure 4-6 Connection of the VT 80 to the BN 3500

When the data is collected, we convert the record from a (.wave) format to a (.csv) or a (.xlsx) format and we utilize MATLAB to apply the signal processing steps cited in the chapter 3.

4.5 Case of study:

During operating of a centrifugal compressor type "BCL-606-A" for the central boosting station, a high level of vibrations was observed(Figure 4-7). This condition was promptly reported to the vibration analysis service, and the maintenance team was mobilized to diagnose and locate the issue.

Note that this machine was maintained by changing the coupling,

The vibration analysis expert proposed a coupling reinspection and alignment reading .

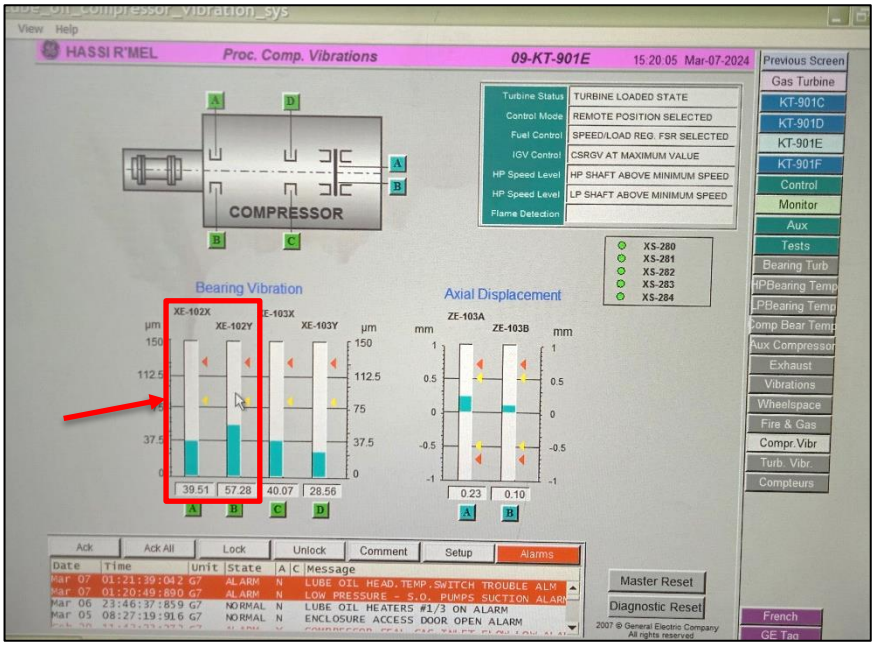


Figure 4-7 Bearing vibration µm -on line monitoring-

This state ‘’damaged’’ was saved, the data was collected into wave form ‘’time domain ‘’. We convert it into CSV file, and we plot it in MATLAB, Figure 4-10), And we have already saved the other state ‘’ healthy ‘’ and its data was also collected and plotted (Figure 4-9).

4.6 Time domain analysis

In the following we used MATLAB to plot two cases (healthy in blue, damaged in red) with amplitudes (µm) as a function of time (sec) on both directions, X and Y.

In the first Figure 4-8, we represented both states on the same axis, then we separated them in the following two figures (Figure 4-9 and Figure 4-10).

In order to visualize the waveform, we narrowed the time domain and maintained the same chronology in the representation.

Then, based on what we discussed in Chapter 3, we formed a script to calculate the overall indicators (RMS,Peak and peak to peak)when we summarized it into the Table 4-1

From the X direction **From the Y direction**

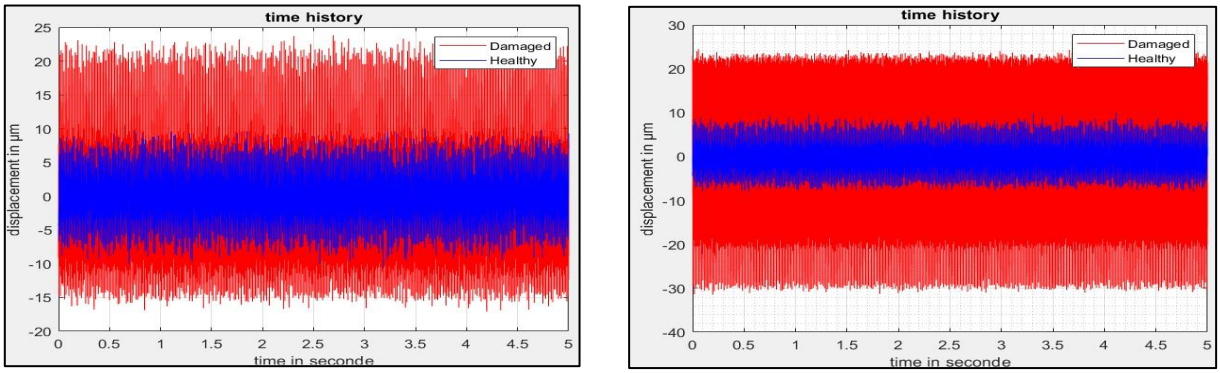


Figure 4-8 Healthy & damaged states superimposed in the same direction

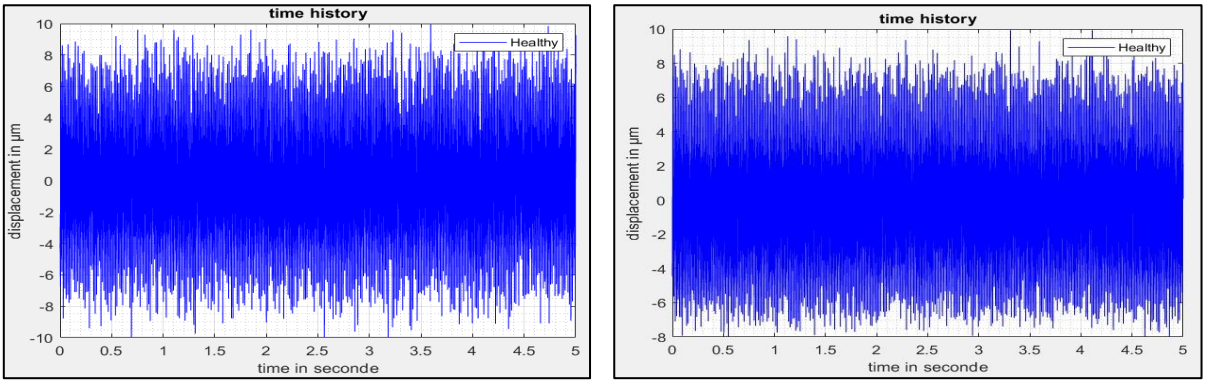


Figure 4-9 Healthy state X&Y direction

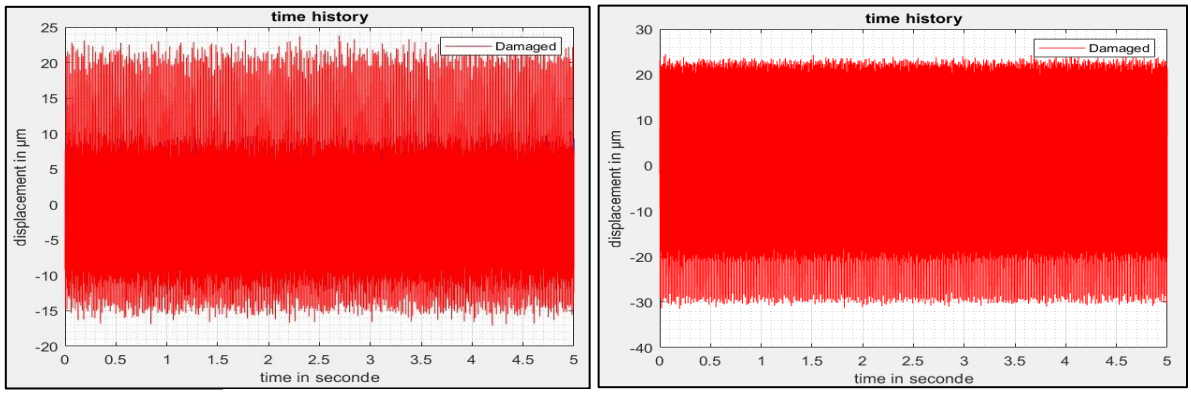


Figure 4-10 damaged state X&Y direction

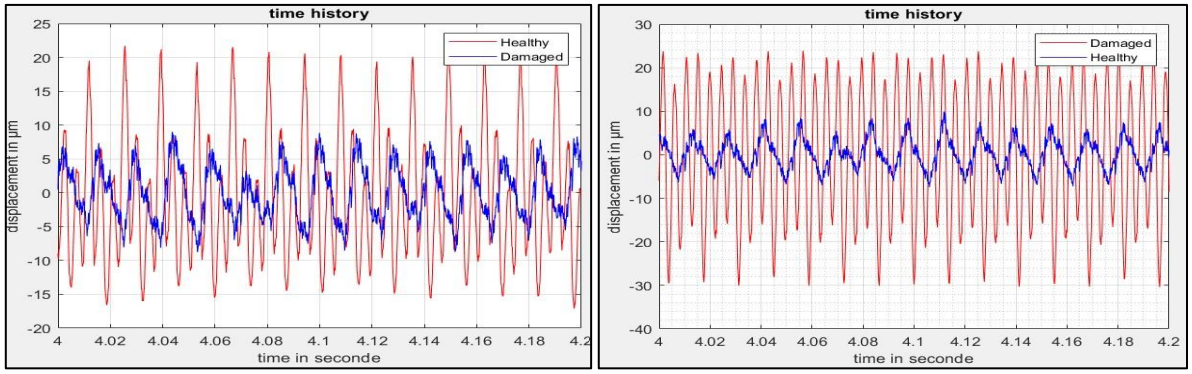


Figure 4-11 Zoom into Healthy & damaged states superimposed in the same direction

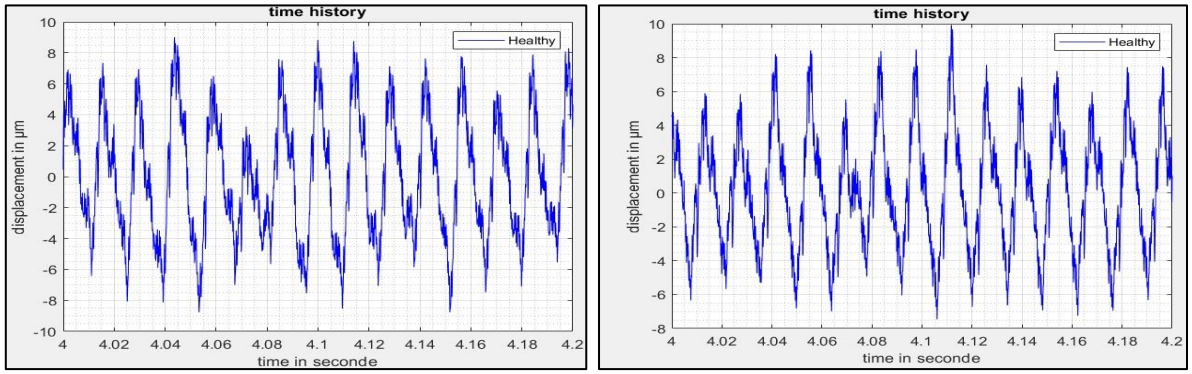


Figure 4-12 Zoom into healthy state X&Y direction

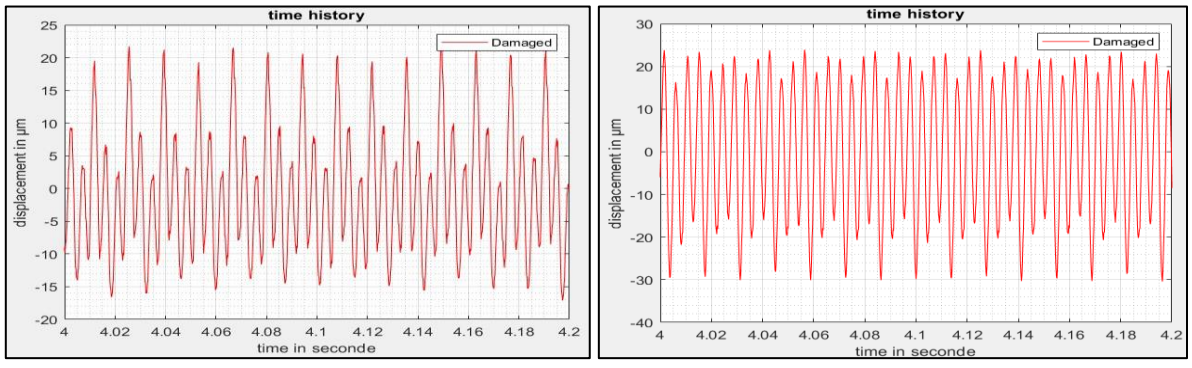


Figure 4-13 Zoom into damaged state X&Y direction

		X direction	Y direction
Healthy	Peak (µm)	10.70	9.93
	Peak to peak (µm)	20.65	18.10
	RMS (µm)	3.84	3.46
Damaged	Peak (µm)	25	31.5
	Peak to peak (µm)	42.20	56
	RMS (µm)	9.39	15.52

Table 4-1 Global indicators for both healthy and damaged states

4.6.1.1 Interpretation of the recorded values

As we see, in the figures and in the table, the amplitudes in the damaged state ‘’peak, peak to peak & RMS ‘’ have increased compared to the healthy state.

Also, if we compare the wave forms, we can observe a new shape totally different from the old one.

4.7 Orbital analysis

Since we have recorded values from two orthogonal directions (X and Y) , for both states, we can plot the orbit (Figure 4-14) of the healthy and damaged states using only the first 1024 values.

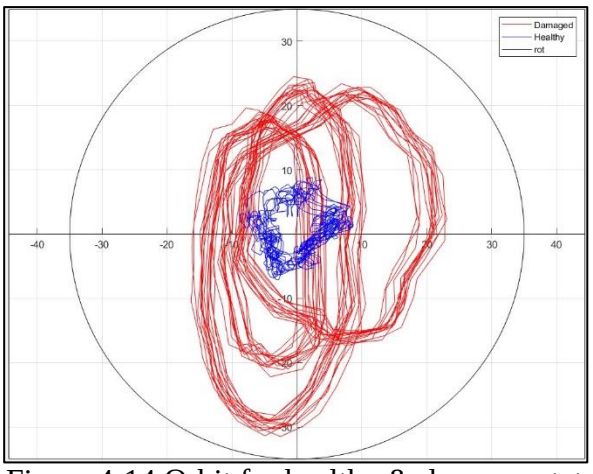


Figure 4-14 Orbit for healthy & damager states

4.7.1.1 Interpretation and orbital analysis

According to Figure 4-14, the disparity in form and amplitude between the two states is evident, indicating a potential risk of damage on both bearings and shafts in such circumstances.

4.8 Signal processing using MATLAB

To diagnose the vibratory level of the machine across the four cases of healthy and damaged states in both X and Y directions, we use MATLAB to implement signal processing steps. This entails initial steps of loading the data into matrices and saving it into files (.mat), followed by processing to derive the final spectrum.

Next, the data is segmented into samples, each comprising 2048 values. Employing a windowing technique on each sample, we then apply the FFT function for transformation. Following this, averaging is applied, optionally with overlap, across varying amplitudes. Ultimately, this process yields a spectrum, crucial for diagnostic assessment and decision-making.

To observe the differences between window types, we will begin with the Hanning window, followed by processing it with a rectangular window. We start with the healthy state, considering both the X and Y directions.

4.8.1.1 Example of application of windowing to a direction

To avoid repetition, we take one table of data (example 102 X damaged) and we will apply hanning windowing with different overlap factor 'OF'; OF= 0 (Figure 4-15), OF= 0.2 (Figure 4-16) and OF= 0.5 (Figure 4-17)

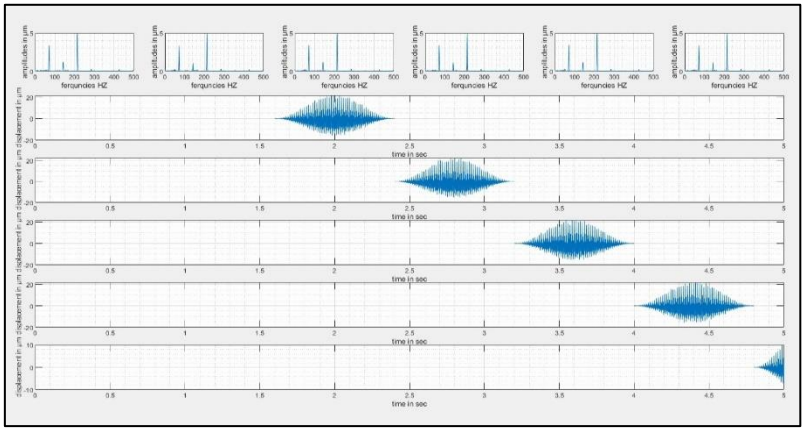


Figure 4-15 Hanning windowing with OF=0

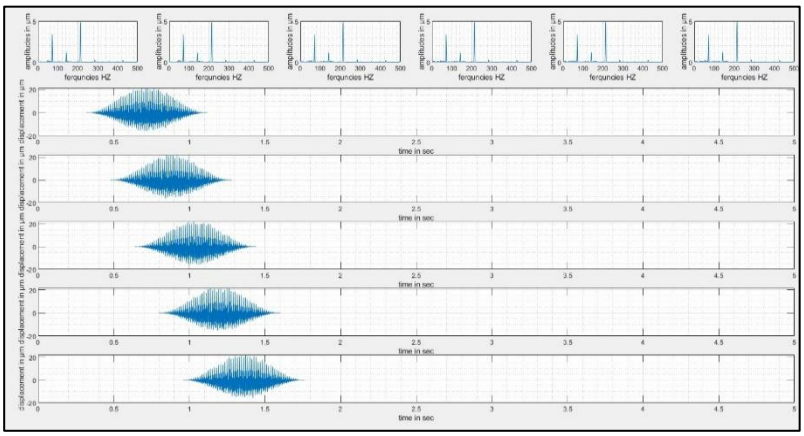


Figure 4-16 Hanning windowing with OF=0.2

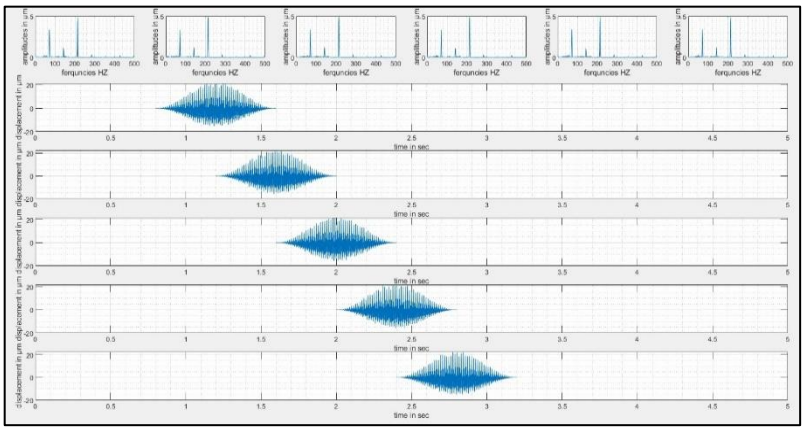


Figure 4-17 Hanning windowing with OF=0.5

For each window we will obtain a spectrum, In the Figure we can see that we have multitude of values of amplitudes for the same frequency example for (1X=70,8 HZ equal to 4 248 RPM) we obtained (3.4,3.38,3.36,3.34 and 3.39) , then we superimposed it in the same axes just to see the importance of averaging.

The next step is to calculate the averaged frequencies and plot it to obtain the final spectrum (Figure 4-20)

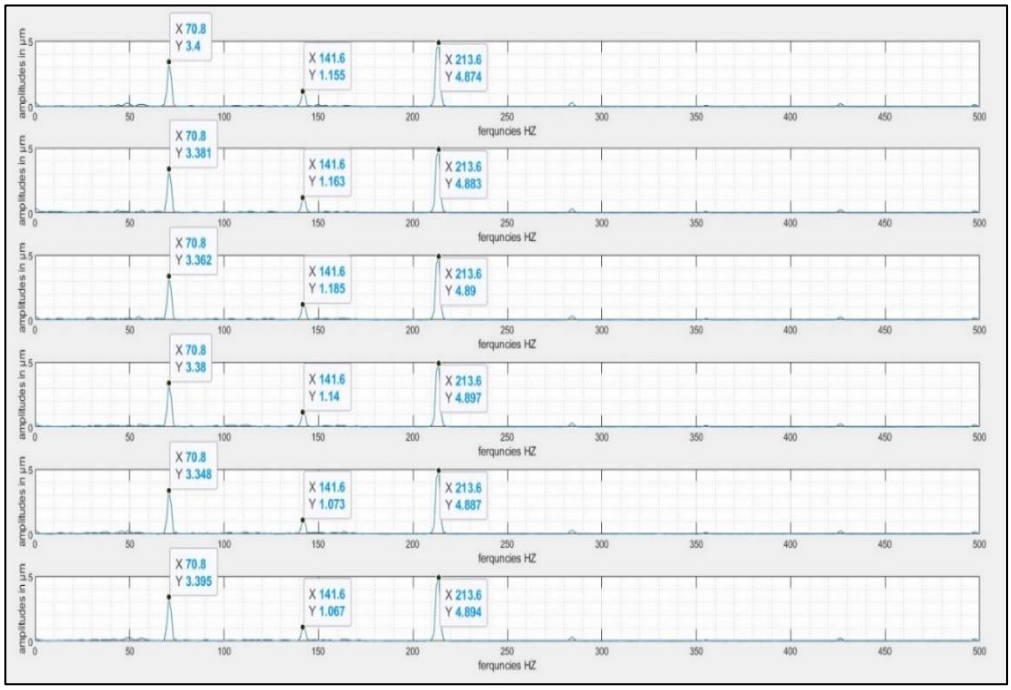


Figure 4-18 Difference between obtained spectra after windowing

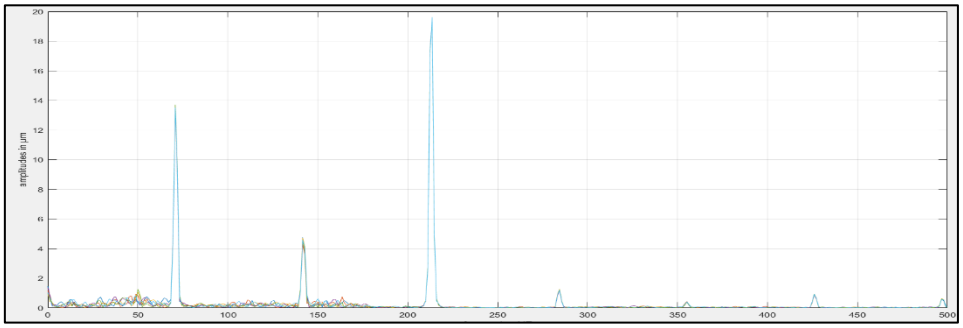


Figure4-19 Superimposed spectrums obtained after windowing

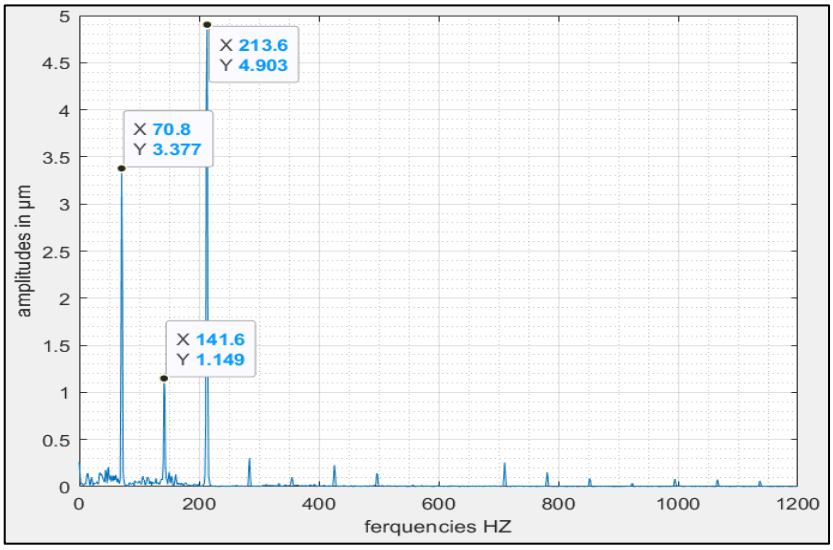


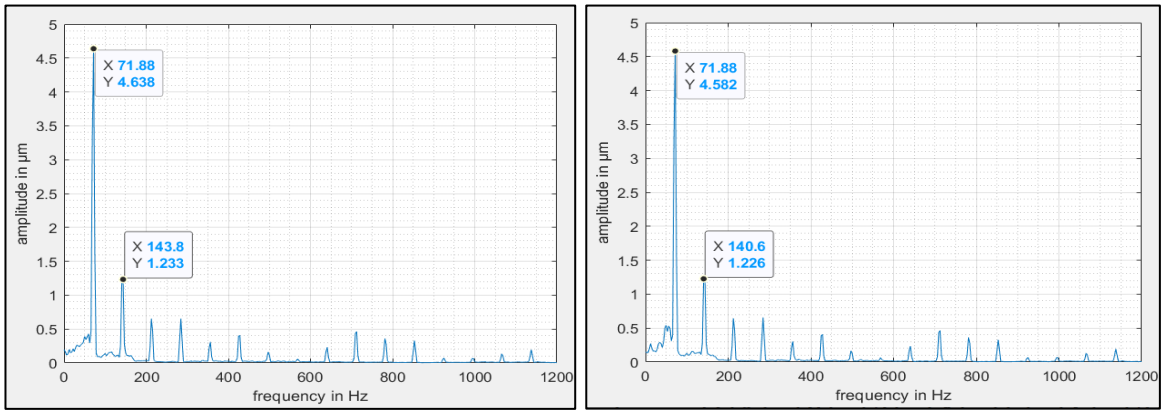
Figure 4-20 Spectrum obtained after averaging with factor overlap FO=0

Finally, we will apply the same steps to get a final spectrum useful for diagnosis.

4.8.1.2 Comparative Analysis of Spectra with Different Overlap Factors and window types

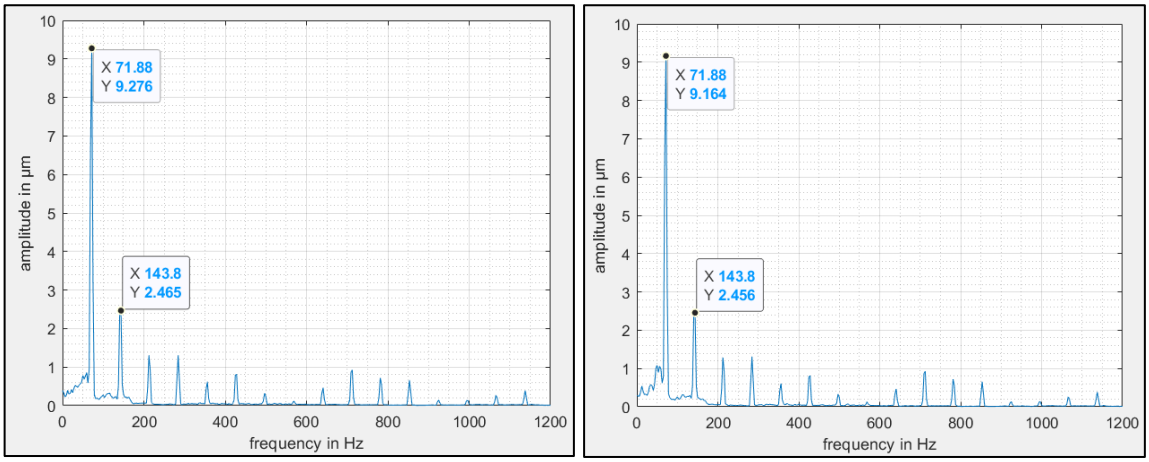
4.8.1.3 Healthy state From X direction RPM=4 308

In the next figures, we represent spectrum obtained from the X direction using a Hanning window as a function of peak amplitude. The Figure 4-21 (a) corresponds to OF=0, while the (b) corresponds to OF=0.5. Then, in the subsequent figures (Figure 4-22), we represent the spectrum as a function of peak-to-peak amplitudes.



(a) (b)

Figure 4-21 Spectrum from 102X, Pk, (a):OF=0 , (b): OF=0.5

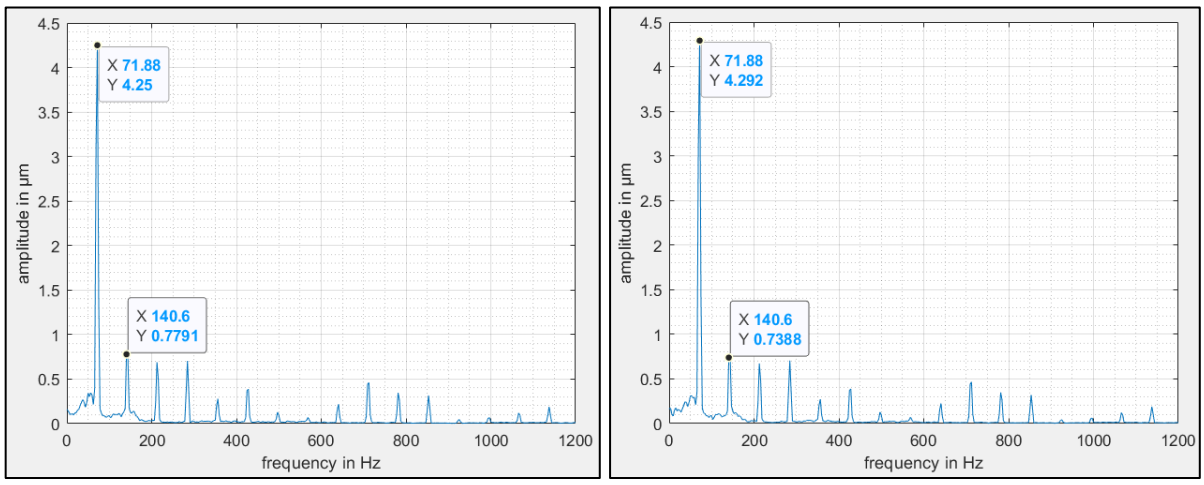


(a) (b)

Figure 4-22 Spectrum from 102X, Pk-Pk, (a):OF=0 , (b): OF=0.5

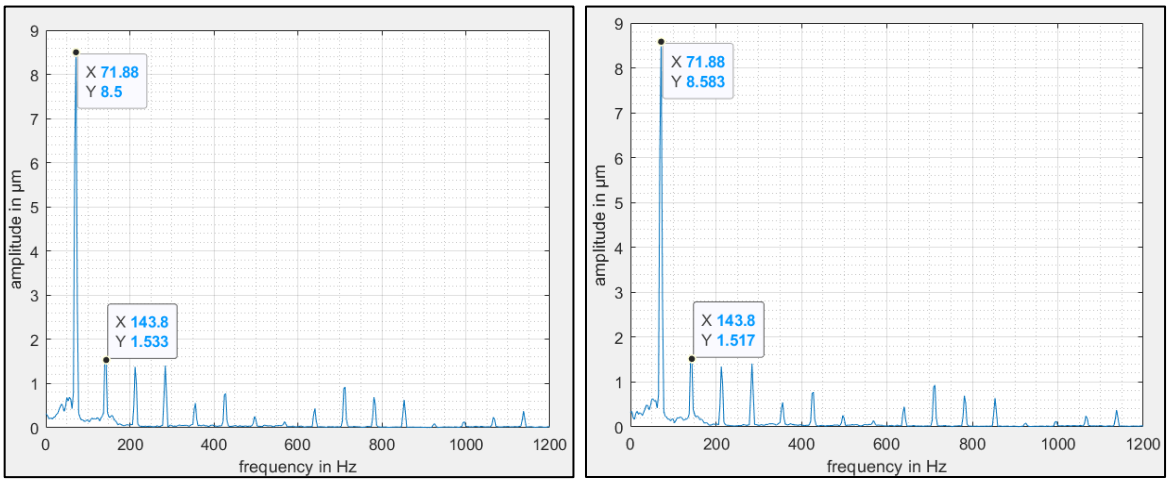
4.8.1.4 Healthy state from Y direction RPM=4 308

The same procedure as before, with the only distinction being that it's from the Y direction, 102 Y we obtain the following figures



(a) (b)

Figure 4-23 Spectrum from 102Y, Pk, (a):OF=0 , (b): OF=0.5

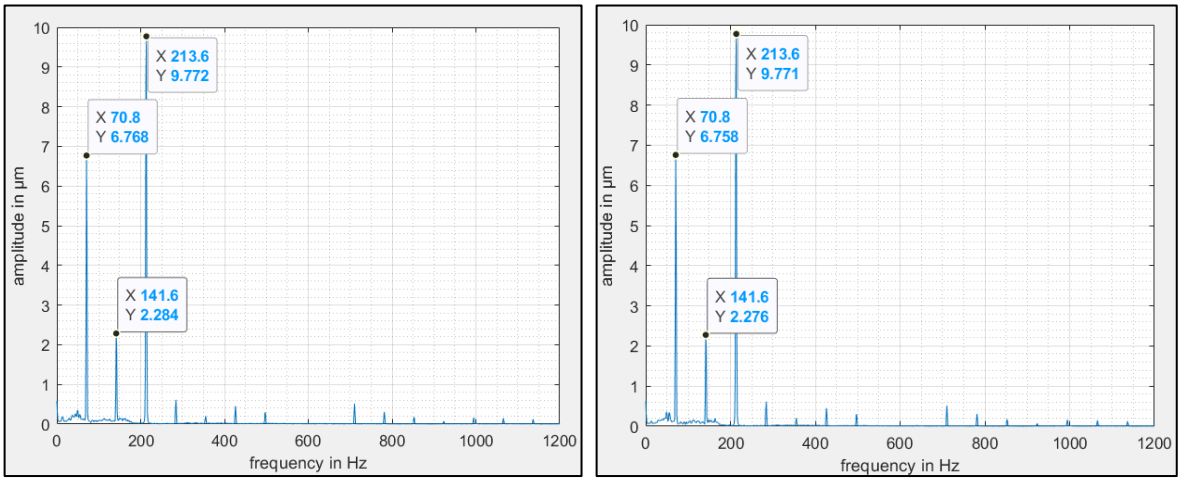


(a) (b)

Figure 4-24 Spectrum from 102X, Pk-Pk, (a):OF=0 , (b): OF=0.5

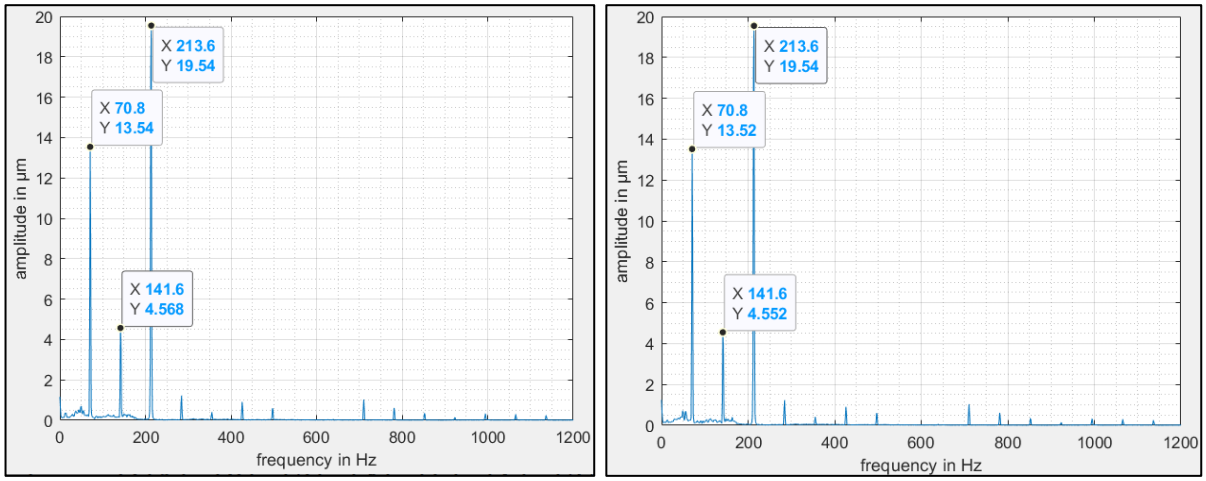
4.8.1.5 Damaged state from X direction RPM= 4 248

Using data from the damaged state, starting with 102X, follows the same procedure as before, we obtain the figures (Figure 4-25 and Figure 4-26)



(a) (b)

Figure 4-25 Damaged, spectrum from 102X, Pk, (a):OF=0 , (b): OF=0.5

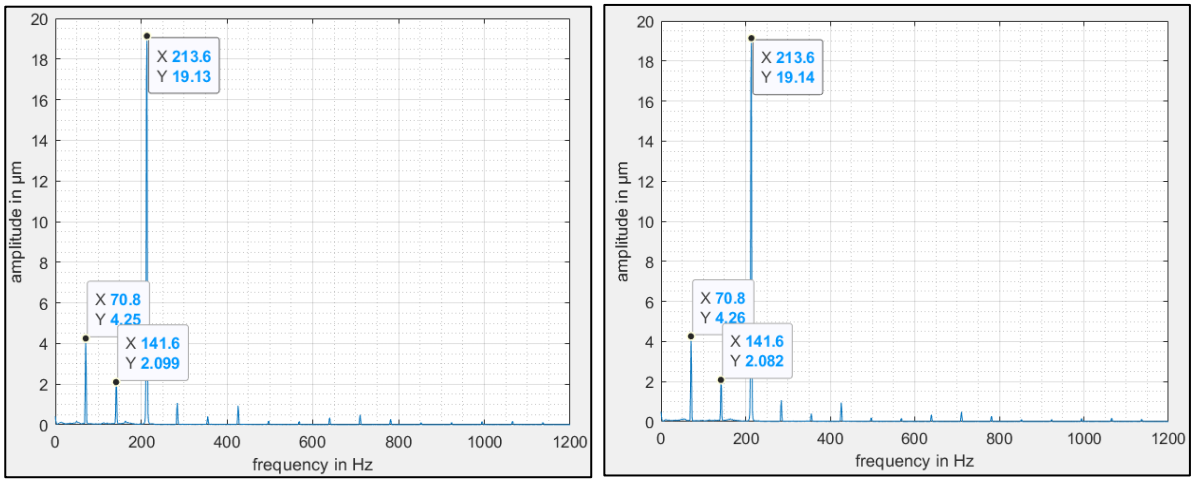


(a) (b)

Figure 4-26 Damaged, spectrum from 102X, Pk-Pk, (a):OF=0 , (b): OF=0.5

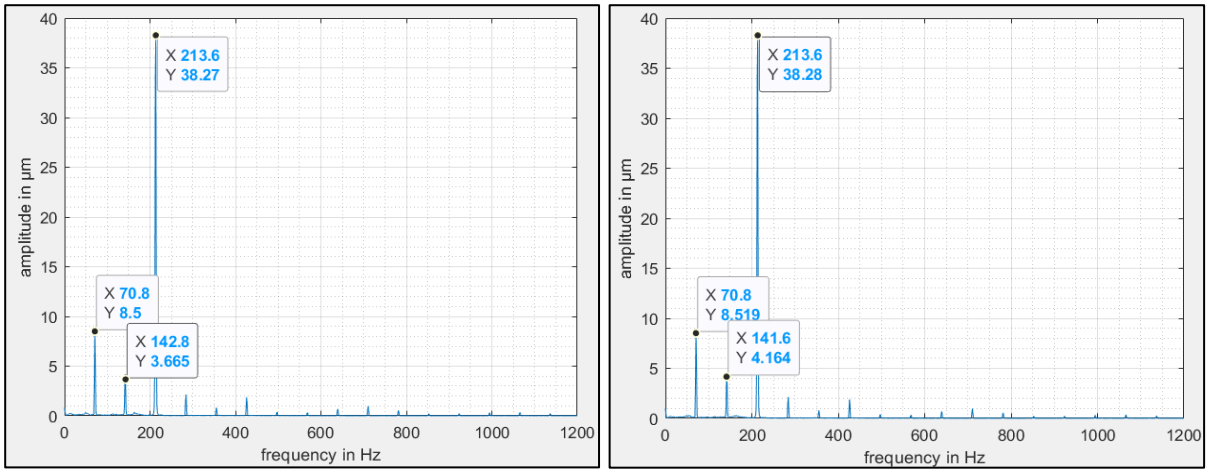
4.8.1.6 Damaged state from Y direction RPM= 4 248

Using the data from the damaged state, from 102Y probe, follows the same procedure as before, we obtain the following figures



(a) (b)

Figure 4-27 Damaged, spectrum from 102Y, Pk, (a):OF=0 , (b): OF=0.5



(a) (b)

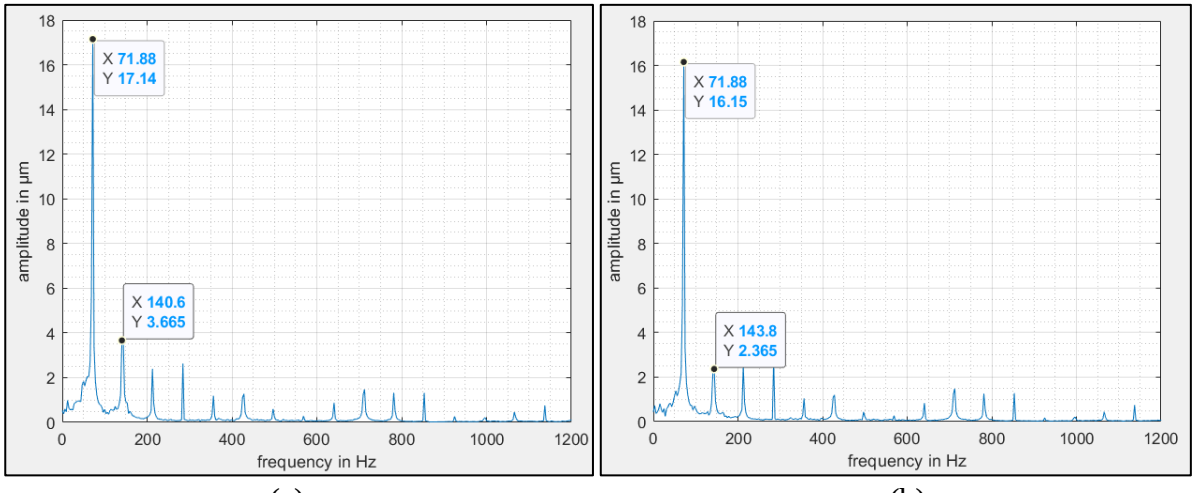
Figure 4-28 Damaged, spectrum from 102Y, Pk-Pk, (a):OF=0 , (b): OF=0.5

4.8.1.6.1 Interpretation of results

Analysing the above steps applied to the signal, we found no notable distinction when employing overlap. Hence, for subsequent analyses, we opted to utilize a 'rectangular window' function, maintaining the overlap factor unchanged (equal to 0.5) to mitigate redundancy.

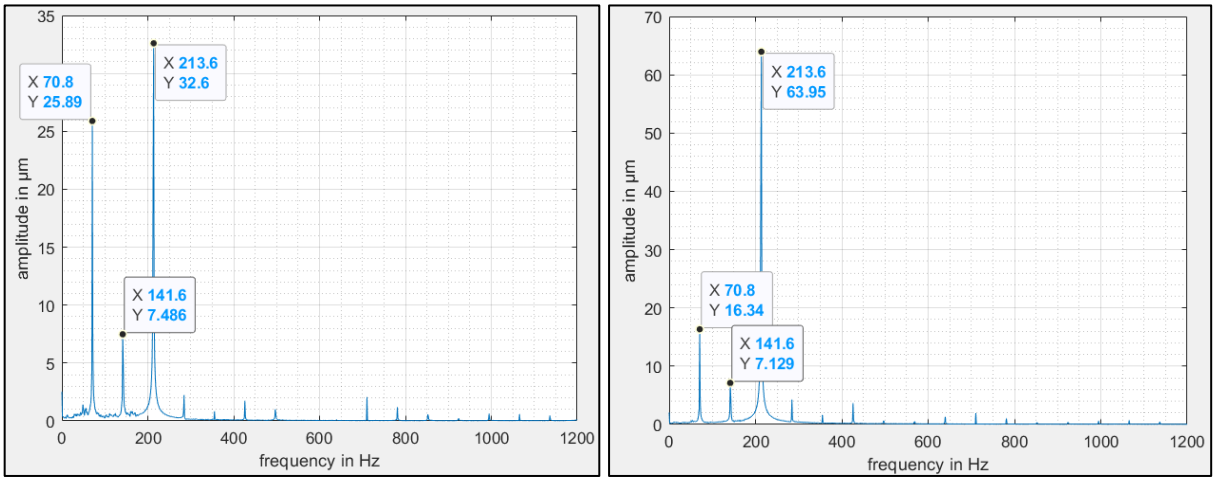
4.8.1.7 Spectrums from a rectangular window:

Now we apply a rectangular window with overlap factor equal to 0.5, to get a spectrum as function of peak-to-peak amplitudes, we obtain the following (Figure 4-29 and Figure 4-30)



(a) (b)

Figure 4-29 Spectrum healthy from ,(a):102X, (b):102Y,



(a) (b)

Figure 4-30 Spectrum damaged from ,(a):102X, (b):102Y,

4.8.1.7.1 Interpretation of results

We can observe the difference between the window function used ‘’hanning and rectangular ‘’ in term of amplitudes, However, the rectangular window is also called no windowing.

The presence of high amplitudes at 3X, 2X, and 1X in the damaged state indicates significant stress on the coupling. Furthermore, the orbit pattern suggests misalignment issues.

Based on our evaluations across time domain, orbital analysis, and frequency domain, we will proceed with the following decisions.

4.9 Diagnosis and decision making

Based on the spectra and orbit data obtained following the anomaly, the following recommendations are made:

- Immediate shutdown of the machine.
- Inspection of the coupling.
- Alignment reading

4.10 Corrective action

Before disassembling the coupling, a thorough examination of the coupling drawings was conducted, revealing that the length of the new coupling exceeds that of the old one by 8 mm (refer to annexes). Consequently, it is inferred that a misalignment occurred following the thermal expansion of the coupling assembly. While these couplings are designed to accommodate some misalignment, simulation indicates an increase in amplitudes post-expansion.

Based on the provided drawings with a new length of 838.91 mm and a thermal expansion of 2.95mm, it is deduced that after thermal expansion, the coupling loses its primary characteristic of absorbing misalignment defects due to its inherent flexibility. Subsequently, it transitions to a rigid state, leading to rotational behavior akin to that of a crank rod on both sides (Figure 4-31).

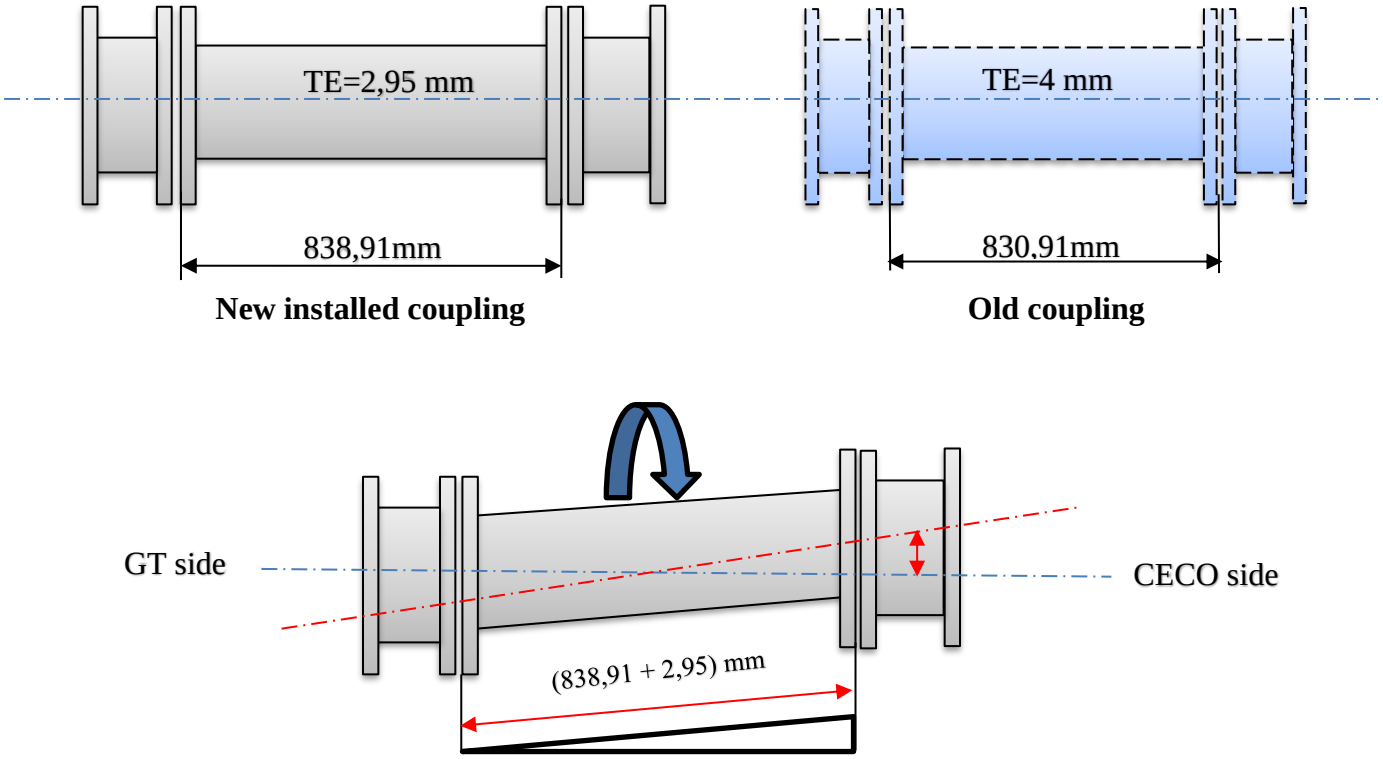


Figure 4-31 New and old coupling length, and shape after thermal expansion

4.11 Conclusion

In this chapter, we worked on a real-life scenario where we used the necessary means to acquire the signal, convert it into numerical data, and then created algorithms in MATLAB to process this signal. These algorithms simulate what the software Report & Route Manager does, starting from signal segmentation into samples, creating windows, transforming them into multiple spectra, and then calculating the average to obtain a single spectrum. To observe the difference between the obtained spectra, we used two windows and two overlap factors. Then, we used the final spectrum for detection and appropriate decision-making.

GENERAL CONCLUSION

GENERAL CONCLUSION

In conclusion, this master's thesis has demonstrated the critical importance of vibration analysis in the maintenance and operation of centrifugal compressors within Algeria's oil and gas sector. Through a comprehensive study that spanned from the theoretical underpinnings to practical application, the research has underscored the strategic role of predictive maintenance techniques in ensuring uninterrupted production processes.

The thesis has successfully bridged the gap between theory and practice by applying advanced signal processing methods, particularly spectral analysis, to monitor and diagnose equipment anomalies. The use of MATLAB software to process vibration signals has proven to be an effective tool for detecting a wide array of potential defects in rotating machinery, such as unbalance, looseness, and misalignment.

By focusing on a real-life scenario at SONATRACH Hassi R'mel, the thesis has provided valuable insights into the application of vibration analysis as a predictive maintenance tool.

The methodologies and technologies employed have not only facilitated the detection of defects but have also enabled informed decision-making regarding compressor maintenance.

The knowledge and experience gained from this project could be invaluable, contributing to the body of work in mechanical engineering and could serve as a reference for future operations.

The thesis stands as a testament to the potential of vibration analysis to enhance the reliability and efficiency of critical equipment in the energy sector, paving the way for more sustainable and cost-effective production practices.

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ANNEXS

ANNEX 1

A1-1Script to plot the wave form & time domain analysis

This script plot the time history and calculate the overall indicators (pk,pk-pk,RMS)

```
clc
close all
clear all

load(' name of data ')
time=name of data (:,1);      %To load the first column from X
displ=name of data(:,2);       %To load the second column from X
plot(time,displ)               %To get a time history figure

xlim([0 5])                   %To get a zoom you can choice[3 3.1]

xlabel('time in seconde');
ylabel('displacement in µm');
title(['time history']);

max_value = max(displ);
min_value = min(displ);

peack = max(abs(displ));              %To calculate PEAK

peak_to_peak= max_value - min_value; % To calculate peak to peak

RMS = rms(displ);                     % To calculate RMS
```

A1-2Script to plot the Orbit

To plot the orbit you must firstly, define a new matrix contain displacements from X & Y directions and save it as a new data.

To have a clear orbit that we can analyses it, we use only the 1024th first values, this technique used in the BK vibro software.

To obtain a clearer figure, you should plot a circle when the orbit is plotted within this circle.

```
clc
clear all
load('asemb_x_y')          % Select data raw from X & Y direction
x1=asembxy(1:1024,1);
y1=asembxy(1:1024,2);
load('dam_assemb_x_y')
```

```
x=damassembxy(1:1024,1);
y=damassembxy(1:1024,2);
t=0:360;                    % Begin_plot_circle
r=35;
X=r*sind(t);
Y=r*cosd(t);
plot(x,y,'r')
hold on                     % End_plot_circle
plot(x1,y1,'b')
hold on
xlim([-40 40])
plot(X,Y,'color', 'black')
grid on
axis equal                  % Unit in the x-direction is equal in
length to one unit in the y-direction
legend('Damaged','Healthy','rot')
ax = gca;            %To place the axes passing through the origin
ax.XAxisLocation = 'origin';
ax.YAxisLocation = 'origin';
```

A1-3The script MATLAB to obtain spectrum

In the following paragraph we paste the script MATLAB used to obtain the figures in the chapter 4, we used the mark percent (%) to explain some lines, to run this script you can copy and paste it into MATLAB but you have to get already a raw data from a sensor (accelerometers , velocimeter, or edge probe) .

Firstly , you have to :

- ✓ Load the data.
- ✓ To define Fs , in our case we have Fs= 12800 Hz, and for damaged we have Fs= 5000 Hz, it depends of the Fmax introduced in the configuration.
- ✓ To define the number of the windows
- ✓ To define the Overlap factor
- ✓ To define data size , it must be equal to 2^N (512,1024,2048….etc).
- ✓ To define the window used for the processing example :(`rectwin(L)` returns a rectangular window of length `L`, `hanning(L)` returns a hann window of length `L`, `hamming(L)` returns a hamming window of length `L`, `flattopwin(L)` returns an `L`-point symmetric flat top window, `blackman(L)` returns an `L`-point symmetric Blackman window).
- ✓ For other details, I introduced it into the script as a comment (%) .

```
clc
clear all
close all
load('Y')                   %Y is the name of the matrix 'data'
time=Y(:,1);                % to load the first column from Y
displ=Y(:,2);               % to load the second column from Y
fs=12800;                   % frequency sample = 2.56*Fmax
N=6;                        % number of window
overlap_factor = 0.5;       % Overlap factor  50% overlap
data_size = [2048, 1];      %definition of the matrix's storage size
values = zeros([ N,data_size]);%to create matrix to save data

 for j=1:N
    k=4096*j*(1-overlap_factor);

     t=Y(floor(k):floor(k+4096)-1,1);
     d=Y(floor(k):floor(k+4096)-1,2);
% floor : Rounds each element of k to the nearest integer less
than or equal to that element.
     L=length(d);
     d=d.*rectwin(L); %Definition of the window see the

        fx=fft(d);     %Caculation of the FFT
        m=abs(fx);     %To get  returns the complex magnitude.
        m_os=m(1:L/2);%To avoid mirror effect of the FFT
        m_mag=4*abs(m_os)/(L/2);     %To calculate amplitudes
%       f=(0:L/2-1)*fs/L;            %To creates bins,delete '%'
when you want to activate the (* & **)
        values(j, :, :) = m_mag;     %Matrix to save data

% *To see how it average delete '%'
%      subplot(N,1, j)
%      plot(t,d)
%      xlabel('time in sec');
%      ylabel('displacement in µm');
%      xlim([0 5]);
%      grid on
%      grid minor
%**To show the diff between spectrums delete '%'
%     subplot(N,6, j)

%     plot(f,m_mag);

%     xlabel('frequencies HZ');
%     ylabel('amplitudes in µm');
%     xlim([0 1200])     %To limit frequencies axis
%     grid on
%     grid minor
```

```
%     hold on             %Use it when you need to show all
spectrums in one,but you have to make a '%' in the first subplot

  End
Inverse_matrix = values'; % to inverse matrix
sum_line = sqrt(sum(values'.^2, 2)/N);%to average
f=(0:L/2-1)*fs/L;
plot(f,sum_line);
xlim([0 1200])
xlabel('frequency in Hz');
ylabel('amplitude in µm');
% title(['spectrum with windowing and averaging']);
grid on; % Activate the grid
grid minor %To activate finite
```

A1-4 Design an application for signa processing

A1-4-1 Objective

To develop an interactive application in MATLAB App Designer that facilitates the analysis and processing of vibration signals. The app will include features such as importing data, applying window functions, visualizing signals, and performing basic signal processing operations.

A1-4-2 Steps to Create the Application:

- ✓ **Open MATLAB App Designer**

Launch MATLAB.

Navigate to APPS > Design App> select Blank App to start a new application.

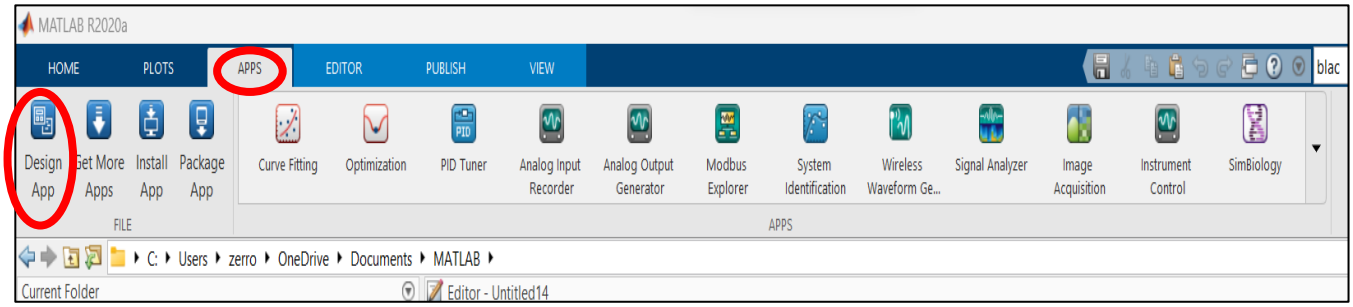


figure 1 Taskbar

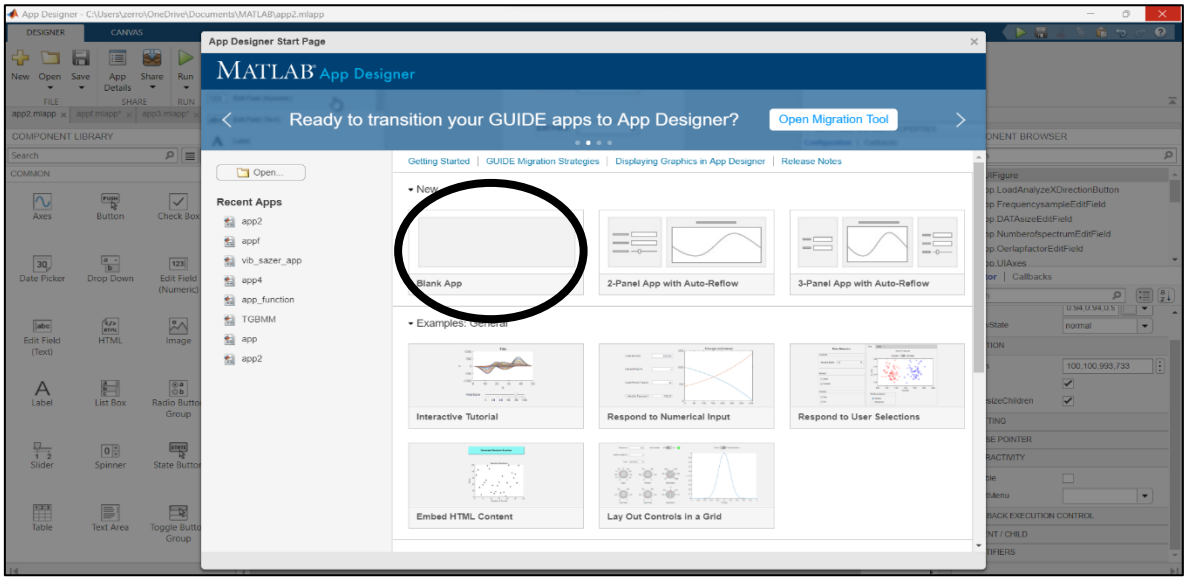


figure 2 App designer start page

- ✓ **Design the User Interface**

Examples

Numeric Edit Field: For inputting parameters such as the type of window function.

Buttons: To trigger actions like loading data, applying processing techniques, and plotting signals.

UIAxes: For displaying plots of the original and processed signals.

Drop-down Menus: For selecting processing options or window functions.

File Load Button: To allow users to load vibration signal data from a file.

- ✓ **Set Up Callbacks and Functions**

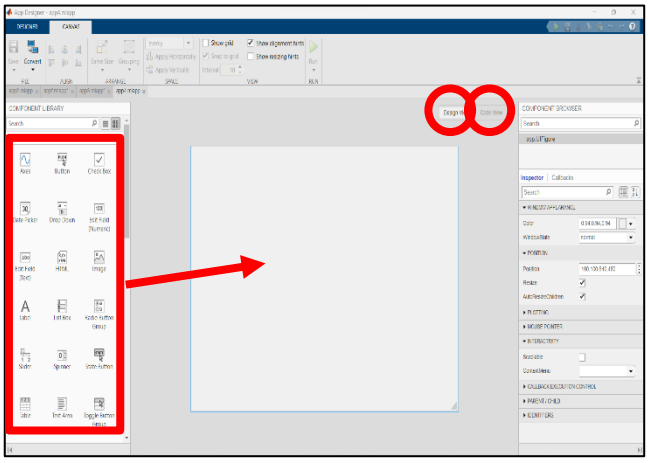


figure 3 App designer design view

After following these steps, we could design an app when it summarize all precedent script and steps using in signal processing we called it SIGNAPRO, and we convert it as an executable file The following figure represent the logo of SIGNAPRO application



figure 3 The logo of the app & start picture

Then we have to designed it as a summarize, and I take you with the result

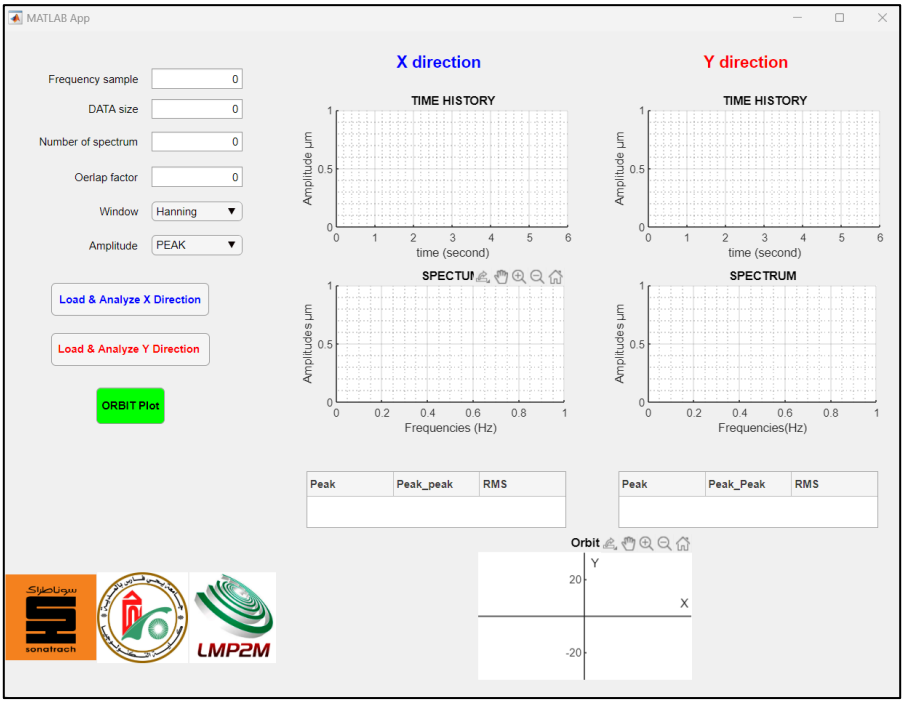


figure 4 SIGNAPRO interface

This interface contains the necessary settings to obtain the final result.

Beginning by the introduction of (Frequency sample, DATA size, Nombre of spectrum to average, overlap factor, windowing and amplitude type).

Then we clique on **Load & analyze X direction**, we get as out put the time history, the spectrum and the overall indicators.

The same steps for Y direction

And to plot orbit from (X and Y) matrix already assembled we just clique on ORBIT Plot to load and plot it in the axe ‘’ Orbit ‘’

The figure bellow shows an example from damaged state.



Figure 5 SIGNAPRO processing done

The advantages of this application include:

- ✓ Time Efficiency in Signal Processing: Significantly reduces the time required for signal processing tasks.
- ✓ Interactive Figure Manipulation: Allows for extensive manipulation of figures, including zooming and moving.

✓ Save Functionality: Offers the capability to save images directly from the application.

See the next figure for more details.

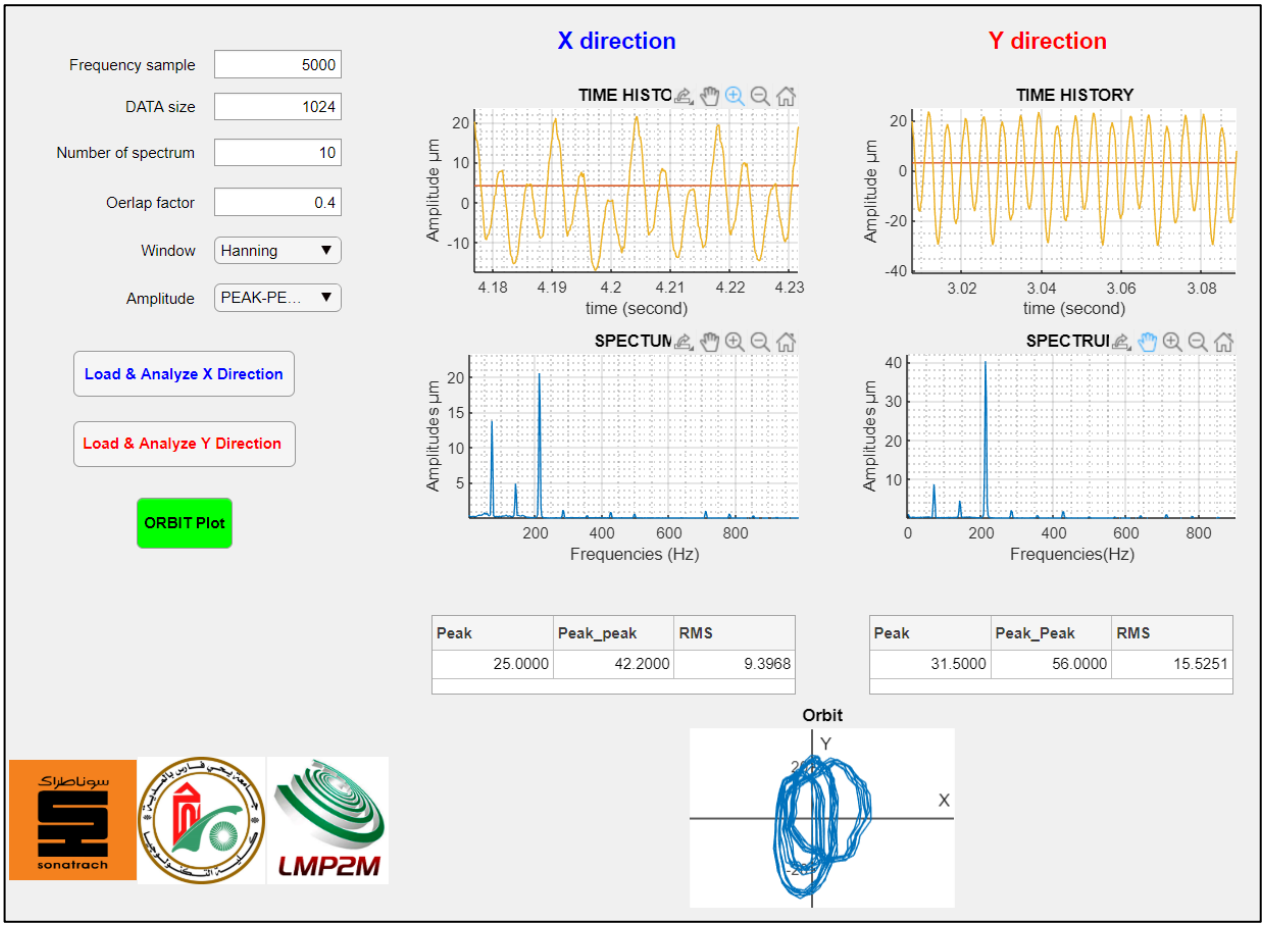


Figure 6 Figures into SIGNAPRO after manipulation

ANNEX 2

A2-1The drawing of the couplings

A2-1-1 New coupling

As we see in the figure bellow, free length = 1630.45 mm, the length of the spacer L=838.91 mm, thermal expansion= 2.95 mm

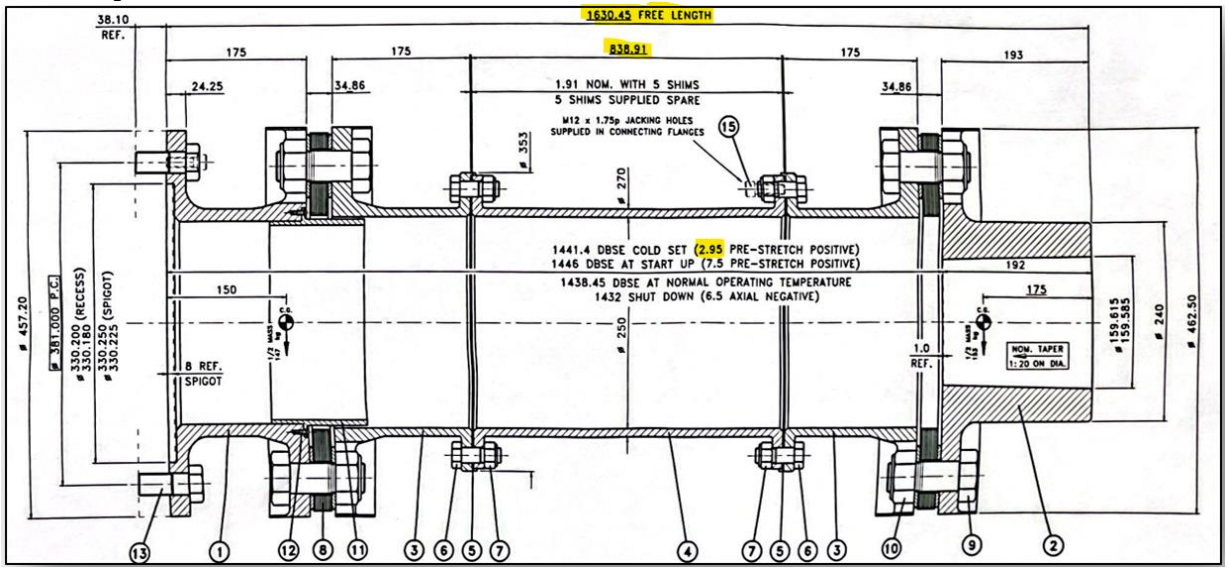


Figure I new coupling

A2-1-2 Old coupling

in the figure bellow, free length = 1622.45 mm, the length of the spacer L=830.91 mm, thermal expansion= 4

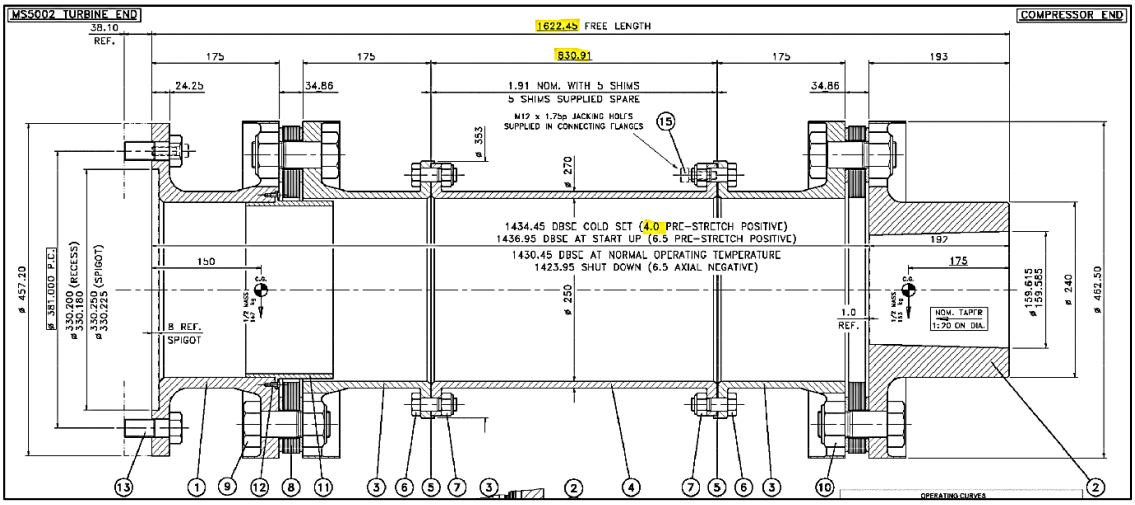


Figure II Old coupling