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## GENERALS NOTATIONS

$\eta_s$  : The ratio between the isentropic power and the real power .  
 $m_1$  : Mass flow rate of the 1st stage.  
 $W$  : Power required at the 1st stage .  
 $h_{12}$  : Enthalpy at the discharge point of the 1st stage .  
 $h_{11}$  : Enthalpy at the absorption point of the 1st stage .  
 $CP_{12}$  : Mass heat at constant pressure of the air at discharge .  
 $T_{12}$  : Air temperature at discharge .  
 $CP_{11}$  : Mass heat at constant pressure of the air at the inlet of the 1st stage.  
 $T_{11}$  : Temperature of the air at the inlet of the 1st stage.  
 $m_2$  : Mass flow in the 2nd stage.  
 $W_2$  : Power required to compress in the 2nd stage.  
 $h_{22}$  : Enthalpy at the discharge point.  
 $h_{21}$  : Enthalpy at the 2nd stage suction.  
 $T_{21}$  : Suction temperature of 2nd stage .  
 $T_{22}$  : Discharge temperature of 2nd stage .  
 $C'$  : is the suction constant  
 $n$  : is the suction coefficient  
 $p$  : is the polytropic efficiency, it is between  
 $W$  : Power required at the 1st stage.  
 $WP$  : the polytropic compression power .  
:is a given of the problem.  
 $L$  : density Kg / m<sup>3</sup>.  
 $r$  : pure gas constant J / mol .K.  
 $V$  : specific volume m<sup>3</sup> / kg.  
 $a_1$  : speed of sound at the entrance of the wheel.  
 $D_1$  : diameter of gravity.  
 $g$  : Acceleration of gravity.  
 $W_p$  : power required for a polytropic compression.

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# **General Introduction**

Today, no one can deny that the maintenance of installations has become neither a choice nor a duty, but an imperative. Maintenance has developed at the same pace as industrial and technological development, and has gone from being an accessory function, limited to cleaning, lubrication and repair operations, to becoming an autonomous function in every company, playing a leading role in improving productivity.

The centrifugal compressors occupy in the different sectors of the industry a very important place, in order to contribute to the improvement of the functioning and the efficiency of this type of devices that we have approached this topic.

This thesis is divided into four chapters:

The first chapter gives the basic concepts and terms of maintenance, its objectives and its role, its different levels and its different types, finally the chapter ends with a description of the maintenance operations

The second chapter presents general information on compressors, it starts with general information, then it deals with the construction of the centrifugal compressor and then it describes the phenomenon of vibration in the organs. It then describes the phenomenon of vibration in the moving parts of the centrifugal compressor and ends with the positioning of the problem.

The third chapter studies the behavior of the compressor, starting with general information about its operation, followed by a presentation of its historical background, its technical characteristics and finally its thermodynamic and vibratory behavior, as well as its working condition at various operating conditions.

The fourth chapter studies the development of a system for the on-line monitoring of the compressor, using artificial neural networks of the multi-layer perceptron type (MLP). The aim of our work is to propose rectifications on the Di-Tronics2 system so that it is able to accurately specify the type of failure that can occur on this compressor.

In our work, we plan to develop and optimize a configuration of a cutting tool wear monitoring system, adapted to turning operations, and based on an optimized neural network, fed with data from cutting force signals.

To this end, we have organized the work into three parts:

In the first part we present a detailed state of the art on the methods of detection of cutting tool wear, namely methods based on the measurement of cutting force, acoustic emission, vibration, temperature (indirect methods) and other less used methods (direct methods) then some notions on the fusion of probes

**Chapter 1**  
**Concept and terms**  
**Of maintenance**

## Introduction:

The maintenance function was designed to attempt to avoid or slow down the phenomena of degradation and wear observed on machines in operation. The different elements of the productive system are discussed: product, agent, tool, relationships between the elements of the productive system, upkeep and maintenance, etc. Definitions of fundamental terms are provided and are an aid to understanding the concept. Subsequently, the properties of the assets (availability and useful life), as well as the states and events relating to an asset (failure, breakdown and state of an asset) are detailed. Commonly encountered maintenance types and strategies are offered to finish.

## I.1 Definition of maintenance

According to the AFNOR X 60-010 standard, maintenance is defined as "all the actions allowing to maintain or to restore an asset in a specified state or in a position to ensure a determined service". In fact, maintenance is to perform operations (troubleshooting, lubrication, repair, improvement, verification, ...) that allow to keep the potential of the equipment to ensure the continuity and quality Chapter 1 Concept and terms of maintenance 1-1 Definition of maintenany of production and safety Of operation. [1]

## I .2 Maintenance objectives

### I .1-1 Cost objectives

- ✚ Minimize maintenance expenses.
- ✚ To provide maintenance within a budget.
- ✚ To have maintenance expenses related to the service required by the installation in
- ✚ Based on their age and usage rate.
- ✚ To tolerate, at the discretion of the maintenance manager, a certain amount of unforeseen expenses.

### I .1-2 Operational objectives

- Maintain the asset in a sustainable manner:
  1. In an acceptable condition
  2. In the best condition
- Ensures maximum availability at a reasonable cost.
- Eliminate failures at any time and at the best cost.
- Maximize the life of the asset.
- Replace the asset at predetermined times.
- Ensure high quality performance of the asset.
- Ensure safe and efficient operation of the asset.
- To obtain the maximum return on investment.
- To keep the asset in a sufficiently satisfactory condition.
- To maintain the property in a state of absolute cleanliness. [2]

### I.2-2. Role of maintenance:

Must ensure the profitability of the company's material investments, maintaining the potential of activities taking into account the maintenance policy defined by the company.

#### I.2-2-1 Short term

Essential objectives :

Reduce the duration of downtime. Reduce the costs of interventions.

### **I.2-2-2. Medium term**

Elaboration of a plan of forecast of the interventions to the immobilization of the equipment's.

### **I.2-2-3. Long term**

Realization of operations directly related to the general policy of the company and end to minimize the scheduling :

Loads.

Inventories.

Investments. [3]

#### 1-3 Different levels of maintenance

The levels of maintenance In the application of maintenance, the various cases to be intervened are divided according to their importance into five levels [6]. A level of maintenance is defined in relation to: The nature of the intervention, The qualification of the intervener, The means implemented. According to "AFNOR X60-010" gives, as an indication, 5 maintenance levels, specifying the responsibility, production or maintenance.

- 1 st Level : Simple adjustment, provided by the manufacturer to the accessible organs without any dismantling or opening of the equipment, or exchange of consumable elements in full safety. - Examples : Exchange of consumable elements such as : fuses, indicators... Degradation of a defective product on an automated machine after the machine has been made safe

These interventions of first level can be carried out by the operator of the good, without particular tools from the instructions of use.

- 2nd Level : Repair by standard exchange of the elements provided for this purpose, and meticulous operations of prevenmaintenance levels, specifying the responsibility, production or maintenance.

- 1 st Level : Simple adjustment, provided by the manufacturer to the accessible organs without any dismantling or opening of the equipment, or exchange of consumable elements in full safety. - Examples : Exchange of consumable elements such as : fuses, indicators... Degradation of a defective product on an automated machine after the machine has been made safe

These interventions of first level can be carried out by preventive maintenance, such as lubrication or control of good functioning. Examples: Greasing of a machine; Control of the good functioning of a heat treatment furnace; Replacement of a solenoid valve on a part loosening system. This type of intervention can be carried out by a technician of average qualification, on site with the portable tools defined by the maintenance instructions.

- 3rd Level: Identification and diagnosis of failures, repairs by exchange of components or functional elements, minor mechanical repairs and all common preventive maintenance operations such as general adjustment or realignment of measuring devices...etc. Examples: -Replacement of a defective contactor coil following an overvoltage; -Dismantling of a pressure gauge giving erroneous indications; recalibration on a control bench, reassembly on the machine.

- 4th Level: All important convective or preventive maintenance work except for renovation and construction. This level also includes the adjustment of measuring devices used for

maintenance and possibly the verification of work standards by specialized organizations. Examples: General overhaul of a compressor; Dismantling, repair, reassembly, adjustment of a lifting winch;

- 5th Level: Renovation, reconstruction, and modernization; by definition, this work is therefore carried out by the manufacturer or rebuilder.

Examples:

General overhaul of a plant's boiler room

Renovations of a packaging line. [4]

## **I.4 Different types of maintenance**

### **I.4-1. Palliative maintenance**

Corrective maintenance activities designed to enable an asset to temporarily perform all or part of a required function. Note: Commonly called "troubleshooting", palliative maintenance is mainly made up of actions of a provisional nature which will have to be followed by curative actions.

Preventive maintenance 1-4-2

Preventive maintenance is carried out at the end of a project, according to predetermined criteria that are significant for the state of degradation of the asset or the service. This maintenance policy is aimed at machines causing a loss of production or unforeseeable downtime costs classified as important for the company. This is the case for machines used in drilling sites. It is therefore advisable to organize a maintenance system aimed at minimizing these often too costly stoppages.

### **I.4-3 Corrective maintenance ;**

All the activities carried out after the failure of an asset, or the degradation of its operation, to enable it to perform a required function, at least temporarily.

Note: Corrective maintenance includes in particular:

- The location of the failure and its diagnosis,
- The repair with or without modification,
- The control of the correct operation.

### **I.4-4. Conditional maintenance:**

Preventive maintenance subject to the crossing of a predetermined threshold that is indicative of the state of degradation of the asset.

Note: The crossing of the threshold can be highlighted by the information given by a sensor or by any other means.

- Tools available for industrial conditional maintenance The integration of the different technologies of predictive maintenance leads to an optimization of the equipment availability. Vibration analysis for the detection of mechanical problems on rotating machines.

Oil analysis on site or with the help of an external analysis laboratory. Temperature measurement, infrared thermography for the periodic control of the electrical and mechanical installation. [5]

## I.5 MAINTENANCE OPERATIONS

-Troubleshooting; Restoration to working order carried out "in situ", sometimes without interrupting the operation of the unit concerned. Troubleshooting is temporary. Troubleshooting characterizes palliative maintenance. Palliative maintenance is characteristic of the 2nd level of maintenance. [6]

-Repair; Done "in situ" or in the maintenance workshop, sometimes after troubleshooting. It has a definitive character. Repair is characteristic of curative maintenance. Curative maintenance is characteristic of the 2nd and 3rd levels of maintenance. [6]

-Inspections: Monitoring activities consisting of periodically noting anomalies and performing simple adjustments that do not require specific tooling, or stopping the production tool or equipment.

-Visits: Monitoring operations which, in the context of systematic preventive maintenance, are carried out according to a determined periodicity. These interventions correspond to a list of operations defined beforehand, which can lead to the dismantling of parts and the immobilization of equipment. A visit can lead to a corrective maintenance action.

-Controls: This operation aims to verify defined criteria or data. It is based on perfectly established verification references.

-Overhaul : All the actions of examinations, controls and interventions carried out in order to ensure the good against any major or critical failure, during a time or for a given number of units of use. Depending on the extent of the operations to be carried out, a distinction must be made between partial overhauls and general overhauls. In both cases, this operation requires the removal of different sub-assemblies. The term overhaul must not be confused with the terms visits, controls, inspections. The 2 types of operations defined (general or partial overhaul) come under the 4th level of maintenance. [7]

-Standard exchange: replacement of a defective part or sub-assembly by an identical part, either new or previously reconditioned, in accordance with the manufacturer's instructions.

## I.6 POSITION OF THE MAINTENANCE STRUCTURE WITHIN THE COMPANY

- ✚ The position of maintenance in the general structure of the company has a considerable influence on the efficiency of this function. Depending on its position in the overall structure, maintenance can obtain better cooperation from other functions, better technical support or create more interest from the management.
- ✚ The position of maintenance in the general structure of the company (or in the organization chart of the company), as well as its internal organization, depends mainly on the following parameters
  - ✚ The size of the company.
  - ✚ The nature of its activity.
  - ✚ The technology AND the complexity of the equipment, installations AND materials used.

- ✚ The quality AND the technology of the product manufactured or the service rendered.
- ✚ The chosen policy.

However, in order for equipment to operate at peak performance, it is necessary to develop maintenance and give it the scope it deserves. Maintenance must be independent of production, to avoid the traditional conflicts between these two structures. It must have and manage its own budget because, due to its importance, it represents very heavy expenses that must be known and clearly dissociated from general expenses. However, this function must be profitable to justify its *raison d'être*. In addition to this, it is necessary and imperative to know the real costs of maintenance per material entity or service provided in order to be able to act either on budgetary factors or on technological factors in order to optimize the efficiency index of maintenance.

The ratios that we will develop later allow us to measure the efficiency. Maintenance must be of high quality. Quality maintenance requires good management, but also a different approach and recognized skills. This new approach requires a change of mentality, the good repairman of yesterday must give way to a confirmed multi-skilled technician whose concern will not only be the immediate but will deal with upstream problems (why this incident? etc.) and will define the policy to be carried out downstream. The guiding principles for the organization of the maintenance function are as follows: ∩

- a) All activities concerning the installation and maintenance of machines are placed under a single authority. This should be the case even in small companies where maintenance will be handled either by the manager himself.
- b) The main person in charge of maintenance should report to as high an authority as possible, preferably the plant manager. It is he who will arbitrate the permanent conflict of interests between production and maintenance.
- c) An organizational chart is useful in establishing the position of maintenance and other functions. In some cases, certain people try to dominate or block relationships. An organizational chart will help resolve this problem.
- d) An organizational chart should not be considered sacred because it only shows the official side of the system.

Unofficially, relationships will depend on personalities. Discussions leading up to the adoption of an organizational chart are always useful. It is especially important that the final flowchart be approved by the management that will support its implementation.

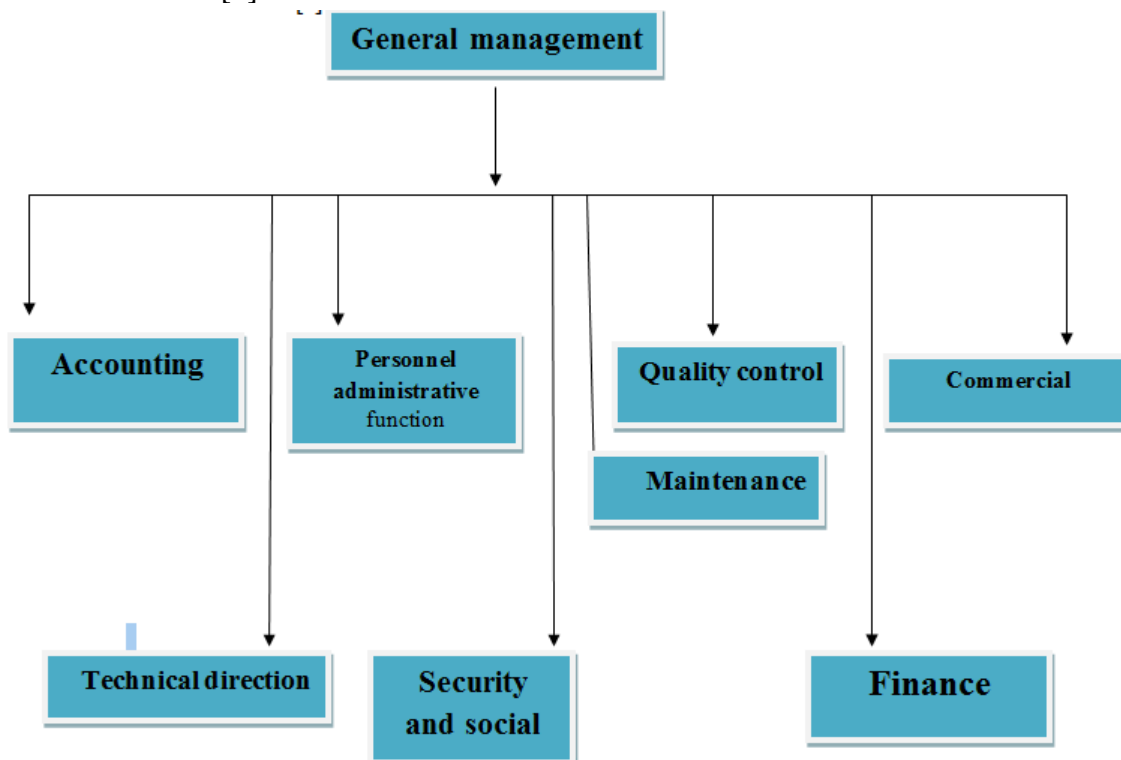
e) Maintenance should not be the responsibility of production. It is a primary function that cannot be managed as a part-time activity by the production manager. If some departments need full-time troubleshooters, these personnel can be allocated to them and still be responsible to maintenance. This is an aspect of decentralization.

f) There is no universal organizational chart that can be adapted to all situations. Each company has its own particular and sometimes changing features. The customs are very different and it is possible that certain functions are not identified separately in small companies,

Currently, any maintenance intervention needs, like any manufacturing process, to be thought out before being carried out. For this reason, the maintenance department must imperatively request an organization of the means to be implemented for the success of its tasks in order to harmoniously carry out the different types of maintenance. There are two trends in the positioning of maintenance in the company:

Centralization, where all maintenance is carried out by one department

. Decentralization, where the entire maintenance department is relieved of certain responsibilities; it is generally manufacturing maintenance that comes under the control of the production and manufacturing departments. The central maintenance department may, at the request of the above departments, lend them its workshop and or personnel to carry out certain work. [8]



**Figure 1.1 Position of maintenance in the company's organization chart**

## Conclusion

Maintenance, as a poorly conducted technology, is becoming a key function of the company. By its effect, it acts as a factor of productivity, element of safety, argument of promotion and reputation of the class of the company. In this chapter, we have exposed a general view on the different types of industrial maintenance as well as their choice which becomes with the time more and more important. In order to be effective, it is first necessary to have as clear an idea as possible of the mechanisms that influence the significant quantities (number of breakdowns, repair times, logistical delays, preventive maintenance costs, material storage costs, communication actions, etc.). These quantities must then be measured and indicators constructed to judge the state of the system. We will devote the second chapter to presenting the study of reliability, maintainability and availability.

**Chapter 2**  
**General information**  
**on compressors**

## introduction:

A compressor is a device that increases the pressure of a substance (usually a gas) by reducing the volume of the substance.

Compressors are used in many applications, most of which involve increasing the pressure inside a gas storage container, such as:

- Compression of gases in petroleum refineries and chemical plants
- Storage of gas in high pressure cylinders
- Cabin pressurization in airplanes
- Air storage for underwater activities
- Filling tires

Other applications include, but are not limited to:

- Refrigeration and air conditioners
- Rail vehicle operation
- Gas turbines
- Powering pneumatic tools
- Pipeline transport of natural gas

## II.1 GENERAL CONCEPT

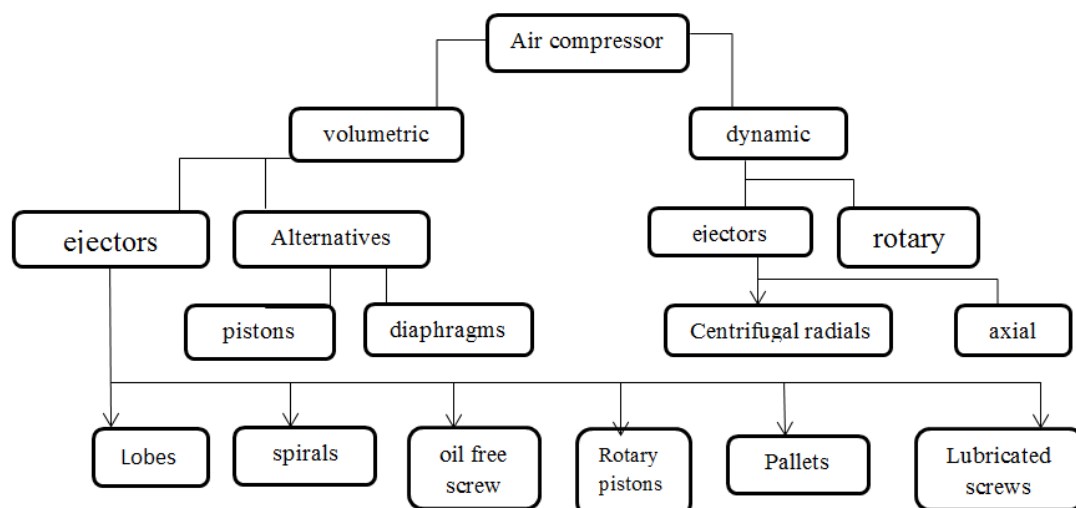
### II.1.1. Definition and classification :

A mechanical compressor is a mechanical device designed to increase the pressure of a gas, and therefore its energy. There are also compressors without any mechanical device, these are the thermo-compressors, more commonly called ejectors.

Classification of compressors :

Compressors can be classified according to several characteristics:

- the operating principle (volumetric, dynamic)
- movement of moving parts (linear, rotary)
- air compressors
- gas compressors [1].



## Figure 1: Classification of different compressor technologies

In general, there are two main types of compressors, positive displacement compressors and dynamic compressors. In the former, the pressure increase is obtained by reducing a certain volume of gas by mechanical action, in the latter, the pressure is increased by continuously converting the kinetic energy imparted to the gas into pressure energy due to the flow around the blades in the impeller

### II.1.2. Choice of centrifugal compressors

- Gas quality
- Gas cleanliness
- Harmfulness of the gas
- Gas flow rate
- pressure (compression ratio).

### II .1-3 Role of centrifugal compressors

They are used for constant and high air flows at relatively moderate pressure, for example in ventilation systems.

Due to their high speed, they are ideally coupled with gas turbines for power generation and aircraft propulsion.

### II.2 Construction of the centrifugal compressor

#### II .2-1 Principle of operation

The gas is drawn into the compressor through the suction flange, enters an annular chamber called the suction scroll and converges uniformly towards the center in all radial directions.

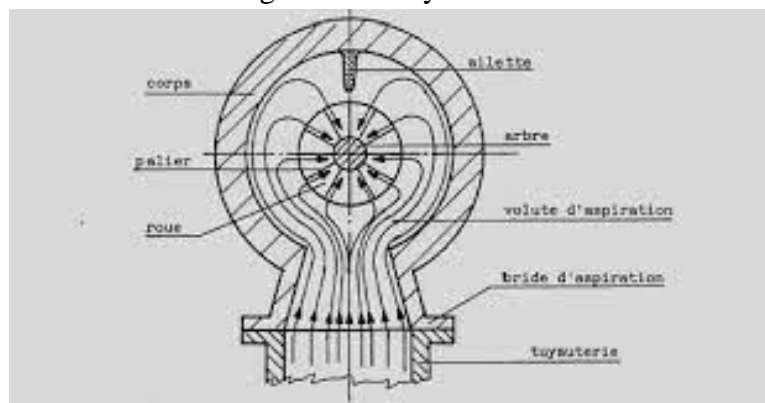
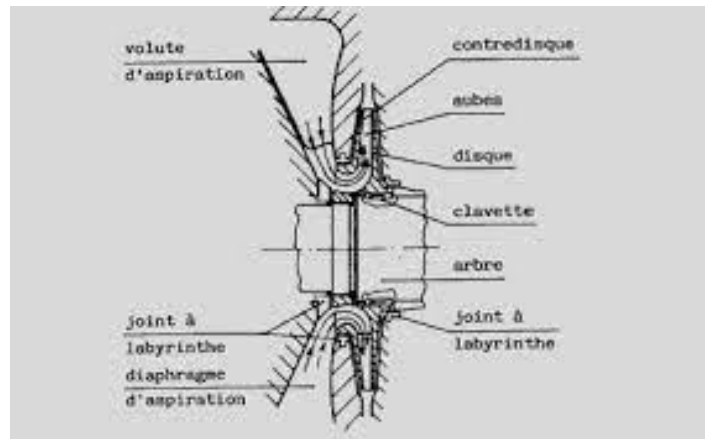


Figure 2: Gas flow at the compressor inlet suction flange

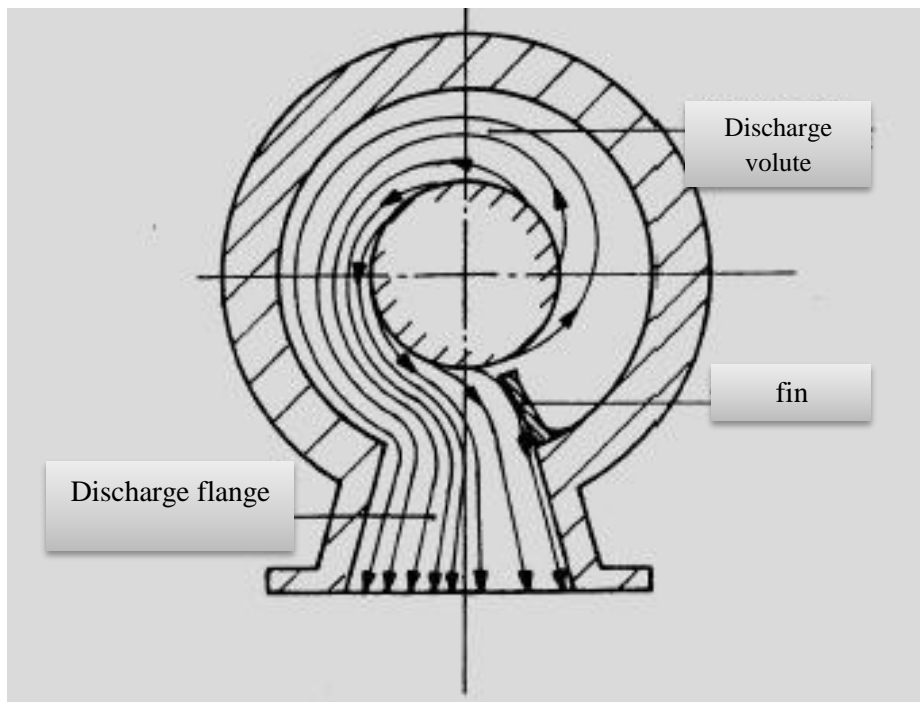
In the annular chamber on the opposite side to the suction flange, there is a fin to prevent gas vortices from forming.

The gas enters the suction diaphragm and is sucked in by the first impeller. The impeller pushes the gas towards the periphery increasing its speed and pressure; the speed at the outlet will have a radial and a tangential component. Then, with a spiral movement, the gas passes through a circular chamber formed by a diffuser where the speed decreases with an increase in pressure.



**Figure.3 :Path of the gas at the impulse level**

La dernière roue de l'étage envoie le gaz dans un diffuseur qui mène à une chambre annulaire appelée volute de refoulement qui collecte le gaz de la périphérie des diffuseurs et le dirigeant vers la bride de refoulement, près de cette dernière il y a une autre ailette qui empêche le gaz de continuer à retourner dans la volute et qu'il envoie à la bride de refoulement. [2]



**Fig.4: Discharge volute**

## **II.2.3.the main components of the centrifugal compressor [3]**

### **1 Diaphragm**

The diaphragms are the dynamic fluid profile of the fixed part of the compressor. They are divided into four types: suction, intermediate, interstage and discharge

### **2.Rotor**

It consists of a shaft on which the impellers are mounted and suitably positioned by means of spacer rings. These are hot mounted and prevent direct contact of the gas with the shaft.

The impellers are of the closed type with backward facing blades. They are hot mounted on the shaft and keyed. Before being mounted on the shaft, each impeller is dynamically balanced and over speed tested at 15% above the maximum continuous speed.

### 3 Shaft:

The shaft is made up of a central part, with a constant diameter, where the impellers and the intermediate bushes are mounted, and of two ends with suitably reduced diameters where the bearings and the end seals work.

Forged steel SAE 4330 is used in the construction of the shafts of all types of compressors. Other manufacturers use ordinary carbon steels. Forged SAE 4330 steel is excellent for hardening and tempering. Shafts of centrifugal compressors of common dimensions, which are made of this material, undergo this type of treatment to the core, while shafts made of ordinary carbon steel are treated only on the surface. This gives SAE 4330 forged steel good toughness and ductility.

The tempering is done at higher temperatures than usual and in any case sufficient to reach a breaking load higher than 108 daN/cm<sup>2</sup> and a yield strength of 6,38 daN/cm<sup>2</sup>.

### 5 Balancing piston :

During normal operation, inside the compressor, a thrust develops on the rotor which must be absorbed by the thrust bearing. This thrust is essentially due to the distribution of pressures acting on the impeller. It is obvious that the  $\Delta P$  developed by the impeller produces an effort towards the suction expressed by the product of  $\Delta P$  by the surface comprised below the seal on the counter - disc. The sum of these thrusts is generally quite remarkable and often exceeds the capacities of the thrust bearing

Therefore a balancing cylinder is a solution to this problem. It is mounted after the last impeller, by putting its opposite surface under the suction pressure and by opportunely dimensioning its diameter. It produces a thrust on the suction side at the discharge so as to balance the thrust coming from the wheels. The balancing is not complete but the residual thrust can be easily supported by the thrust bearing so as not to create inaccuracies in the rotor positioning. There are other thrusts, such as the thrust due to the variation of the gas momentum entering the impeller axially and leaving it radially or the thrust resulting from the non-uniformity of the pressures acting on the impeller in high pressure machines. The width of the balance piston must be such as to support the entire  $\Delta P$  developed by the compressor. The balance cylinder is made of X12C13 steel and hot shrunk onto a wedge key like the impellers

### Thrust Bearings:6

The thrust bearings installed on most centrifugal compressors are of the tilting shoe type and are provided with uniform and distributed load support. The pads work on a collar which is hydraulically mounted on the shaft.

## **II -2-4 Type of sealing device [4]**

### **1.Oil seals**

The purpose of the seals located at both ends of the shaft is to prevent or minimize the escape of compressed gas or the entry of air into the compressor body. The seal can be of two types: labyrinth seal and oil film seal.

## 2. labyrinth seals

Internal seals installed between the stator and rotor assemblies of the compressor and used to reduce gas losses that may occur between areas of different pressure are labyrinth seals. A labyrinth seal consists of a ring with a series of blades on the periphery that have a reduced clearance to the rotor, which minimizes leakage by blocking gas that tends to leak from the shaft ends.

These rings are made in two halves and are made of a light alloy that is corrosion resistant and has a lower hardness than the rotor to prevent damage to the rotor in case of accidental contact.

**Oil seals:** The oil seals consist of two floating rings (high pressure on the H.P. side and low pressure on the B.P. side) coated on the inside with anti-friction metal. Fig. 3. 4 shows a typical drawing of the end of a compressor equipped with several sealing rings on the low pressure side.

The sealing oil, at a pressure slightly higher than that of the gas, enters the annular space between the two rings and passes into the annular space left by the clearance between the rings and the shaft.

### II .2-5 Mechanical seals :

The mechanical seal basically consists of a normally stationary carbon ring kept in contact against a rotating steel collar with the compressor shaft. The contact is ensured by the combined action of elastic elements (springs and bellows) and by the pressure distribution acting on the ring itself.

The contact between the collar and the ring generates heat which must be eliminated by cooling the seal with oil. In order to guarantee the lubrication of the space containing the lubricant film between the collar and the ring, it is necessary to have a high enough differential pressure between oil and gas. In order to maintain this P, it is necessary to create a pressure chamber and therefore it is necessary to have a BP seal between the oil under pressure and the atmosphere.

Mechanical seals are mainly used where it is important to limit the amount of oil that can pollute the gas: in fact the oil loss of the H.P. ring is about 5 to 10 times smaller than the losses of ordinary oil seals.

In case of emergency stop of the compressor due to lack of oil, the seal continues to block the gas, to machine at the stop (Even if in an imperfect way for the possible presence of scratches and wear on the contact surfaces between the collar and the ring).

We can also use a double seal, it is composed of two single seals mounted face to face, an injection of neutral gas is made between the two seals. This injection can pollute the gas of the process, but avoids the rejection of this gas in the atmosphere. The reliability of this packing is totally linked to the neutral gas injection.

### II .2.6 Compressor surge

Pumping is a fundamental phenomenon of dynamic compressors. These machines are characterized by the fact that compression is obtained by energy exchange in the gas set in motion in rows of blades. Pumping is this overall aerodynamic instability of the compressor in its environment, when operating at low flow rates. When the discharge network has been

sufficiently emptied into the suction, the compressor finds new operating conditions to restore the flow in the right direction until a new cycle of instability starts again.

## **II .2-7 Compressor anti-pumping device**

In the event of a decrease in flow rate due to an increase in the pressure ratio, which is the main cause of pumping, the existing devices are designed to :

- Either to artificially increase the flow through the machine.
- Either to decrease the pressure ratio. The principle is that the gas is returned to the suction side by the valve; the action of this valve, called "by-pass", can only be of short duration, because part of the power accumulates in the loop in the form of heat by raising the temperature level a lot (the addition of a cooler avoids this problem); the flow generated by the compressor is therefore the one that goes through the valve.

But using control valves instead of on-off valves. The control system will therefore include a regulator based on automatic techniques.

For recirculation, the gas must be refrigerated to ensure prolonged service without heating the loop and the compressor.

For this purpose, the anti-pumping circuit is usually taken after the cooler, installed at the discharge end, which is already in use during normal operation.

The control system (fig.3.22) includes, in black drawer, instrumentation to measure the flow through the compressor, as well as the suction and discharge pressures. Taking into account the measured pressure ratio, an authorized flow rate is calculated according to the pumping protection limit curve, this value is given as a setpoint for the anti-pumping regulator. The anti-surge controller receives the signal from the flow meter and controls the expansion control valve (dashed blue). 5]

## **Conclusion**

From the earliest days of humans blowing on fires to smelt the metals of ancient times to today's highly advanced pneumatic tools and machines, compressed air has proven to be one of the most useful resources in industrial development.

Many other industries, including energy exploration, food and beverage packaging and dry cleaning also depend on the advancements of today's versatile compressed air systems. From the food we eat to the highly sophisticated automobiles we drive each day, compressed air likely played a role in their creation.

Compressed air has provided industry with countless benefits over the centuries and has increased capabilities in automation and led to the development of more powerful tools. It's also a costly resource that consumes energy to produce the clean airflow needed.

When selecting an air compressor system for your business, it is important to identify what type of compressor will best serve your needs while still delivering the dependability and power required for your operation.

Inefficient compressed air usage can result in costly energy losses and impact your bottom line. In addition, proper maintenance and inspection for air leaks are also essential for keeping your system operating at optimal performance and efficiency.

# **Chapte3**

## **Study of the compressor behavior**

**introduction:**

During the use of turbocharged Diesel engines at low flow, the compressor could operate into his prohibited surge area. This occurrence may induce dangerous instabilities, which result in mechanical, and heat loads that could damage the completely turbocharged engine. In practice, avoiding this risk is done by reducing the boost pressure at low engine speeds and hence reducing the engine torque. In fact, surge is an aerodynamic instability characterized by fluctuations in the average flow through the whole compression system. The mass flow fluctuations at surge can be so large that during a short part of the surge cycle the mass flow becomes negative. The oscillatory loading and unloading of the compressor in surge imposes transient loads on the bearings supporting the compressor shaft and can have disastrous effects overall compression system. Furthermore, surge produces mechanical vibrations and is usually clearly audible. The surge behavior of compressor is defined as a function of, not only the compressor design, but also of the geometry around of compressor. It is well known that a bad design of the compressor inlet may induce surge... Depending on the pressure oscillation levels, the turbocharger can be damaged when operating in deep surge

**III.1 Generalities**

The centrifugal compressor is a machine whose function is to increase the pressure that passes through it.

Through its moving ring, a certain amount of energy is imparted to the incoming fluid during the suction phase. The mobile crowns receive their movement from the motor shaft.

A certain amount of this energy is transformed into a pressure increase, directly in the moving rings, and the remaining part in the diffusers.

The centrifugal compressor consists of an outer casing, which contains the diaphragms, i.e. the various rings mounted on the shaft.

**III. 2 Historical record**

This table shows the compressor failures from the first installations up to now.

Panne N°	Date of failure	Intervention
01	24/02/2017	<p><i>Preventive maintenance of the compressor is high vibration at the weapon displayed on Hxr302 (in the control panel), higher than 75 microns.</i></p> <p><i>Dismantling for maintenance and control of the couplings 1 (between motor and gearbox)</i></p> <p><i>Check the support bearings: on the coupling side; tear off the white metal. Bearing on the external side with play exceeding the normal.</i></p> <p><i>Alignment check before correction</i></p> <p><i>Change of the two bearings on the coupling side.</i></p> <p><i>Adjustment of the axial displacement with new bearings.</i></p> <p><i>Alignment correction: radial</i></p>

		+0.01 _____ 0.07 - 0.02
<b>02</b>	<b>02/11/2019</b>	<ol style="list-style-type: none"> <li>1. Conservation of the old compressor rotor.</li> <li>2. Sandblasting of the rotor with the bearing.</li> <li>3. Checking the condition of the bearing seats and measuring the clearance of the rotor.</li> </ol>
<b>03</b>	<b>21/05/2021</b>	<p>Change of compressor seal rings</p> <ol style="list-style-type: none"> <li>1. Dismantling for the change of the LP sealing rings (02)</li> <li>2. Change of bearings <ul style="list-style-type: none"> <li>• Seal oring (02): 585010292.</li> <li>• Gasket (01mt): 77301210.</li> <li>• Bolt seal (01j): 586010214.</li> </ul> </li> </ol>
<b>04</b>	<b>20/01/2000</b>	<p><i>Opening the compressor for maintenance and inspection with the assistance of the high vibration technician (N).</i></p> <ul style="list-style-type: none"> <li>• <i>Disassembly of the compressor.</i></li> <li>• <i>Balancing of the rotor</i></li> <li>• <i>Checking the labyrinth clearances.</i></li> <li>• <i>Reassembly of the compressor half-shell.</i></li> <li>• <i>Reassembly of the seal, after checks (02): 585010224. Reinforcement of the original bearing surface of the sealing boxes with a Teflon seal. Survey of the compressor clearances and tolerances.</i></li> </ul>

### III. 3 Technical characteristics of the compressor

#### III.3.1 . Operating condition

Compressed gas	Ethylène
1st stage flow Kg/h	7.300
Flow 2nd stage Kg/h	8.800

#### Gas condition at suction

Molecular weight	28.5
CP/CV	According to analgesic diagram
Compressibility	According to analgesic diagram
Pressure (atmosphere)	2.44
Temperature (C°)	-37.2

#### Gas condition at discharge

( Pressure (atmosphere)	27.75
Temperature ( C°)	+120
Shaft power Cv	1.883
Speed t/mn	13.600
Horne Direction of rotation (seen from the drive (side	Horne

#### III.3.2 Les données de bon fonctionnement

Ce tableau représente les donnés de la marche du compresseur

Description des relevés	Unité de mesure	Donne de
Percentage of load	rpm	100
Rotational speed	atm	13.600
Inlet pressure 1st stage	atm	2.44
Intake pressure 2nd stage	atm	5.60
Gas discharge pressure	C°	27.75
Suction temperature 1st stage	C°	-37.2
Suction temperature 2nd stage	C°	-4
Gas discharge temperature	Kg / h	120
Gas flow 1st stage	Kg / h	7300
Gas flow rate 2nd stage	Kg / h	8800
Compression ratio 1st stage	Kg / h	2.3
Compression ratio 2nd stage	Kg / h	4.9
Molecular weight	Kg / h	28.5
Axial displacement of the rotor	Mm	0
Vibration bearing (suction side)	Mm	0
Vibration of support bearing (discharge side)	Mm	0
Thrust temperature	C°	50

Bearing temperature at suction side	C°	50
Bearing temperature at discharge side	C°	50
Oil temperature at discharge side	C°	60
Oil temperature at discharge side	C°	50
Oil temperature Suction Bearing Discharge	C°	60
Oil temperature Discharge bearing relief	C°	60
Oil pressure discharge lubricant	Kg / cm <sup>2</sup>	12
Pressure of oil manifold seal	Kg / cm <sup>2</sup>	9
Oil filter differential pressure	Kg / cm <sup>2</sup>	0.35
Pressure of oil bearing suction side	Kg / cm <sup>2</sup>	1.2
Pressure of oil bearing at discharge side	Kg / cm <sup>2</sup>	1.2
Reference gas pressure	Kg / cm <sup>2</sup>	1.9
Absorbed power	KW	1841
Oil pressure at seals	Kg / cm <sup>3</sup>	2.3/ 6

As a result, there is an increase in the pressure loss due to friction and naturally the compressor cannot work in an optimal and economical way. The operation on this part of the curve is said to be «Choked operation»

### III .4 Determination of the thermal parameters of the centrifugal compressor

#### III. 4.1 The power required for compression

There are two methods for calculating the power required for compression:

- Isentropic method.
- Poly tropic method.

##### III.4.1.1 Isentropic method

The necessary power is given by the following formula:

$$W_1 = m.(h_{2,s} - h_1) \dots\dots\dots(III.1).$$

The index (s) means an isentropic compression (reversible adiabatic), and the indices (1 and 2) mean respectively the entrance and the compressor, m is the necessary mass flow and the fact that a reversible compression is impossible to achieve.

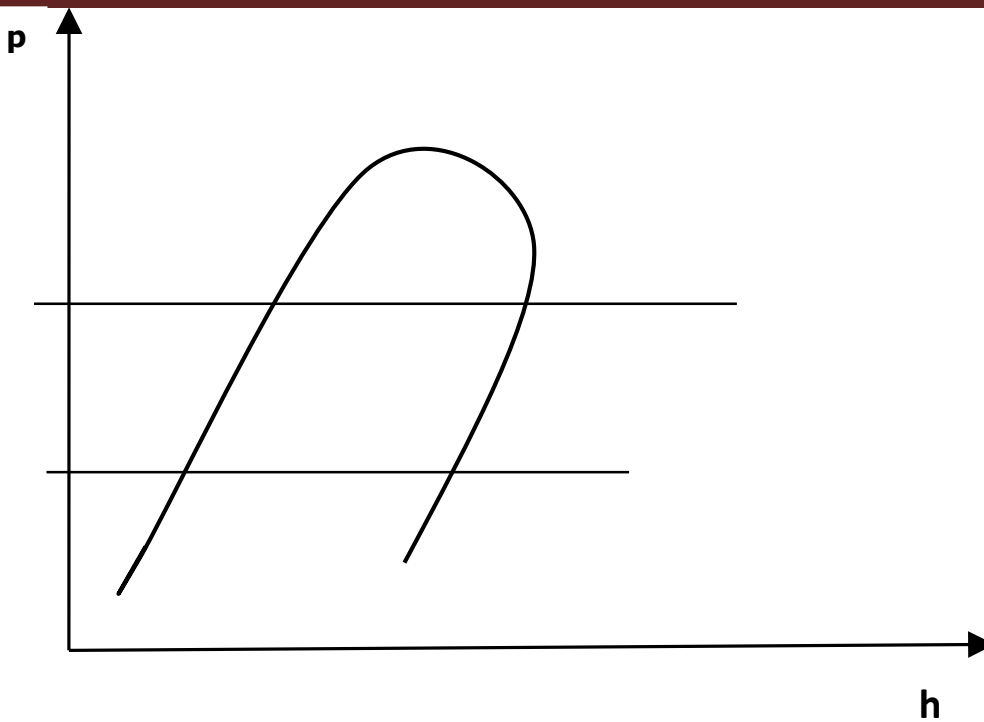
So the real power required for the operation of irreversible adiabatic compression is given by :

$$W_1 = m.(h_2 - h_1)$$

$$= \frac{1}{\eta_s} .m.(h_{2,s} - h_1) \dots\dots\dots(III.2).$$

$\eta_s$ : The ratio between the isentropic power and the real power (value between "0.62and 0.83").

The following figure (3.1) represents the isentropic compression and the adiabatic reversible compression in the pressure curve.



**figure(4.1):** Isentropic and irreversible adiabatic compression

The location 1-2s: represents the isentropic compression.

The place 1-2: represents the irreversible adiabatic compression.

**a)- The power necessary for the compression in the first stage**

$$W_1 = m_1 \cdot (h_{12} - h_{11}) \dots\dots\dots(III.3)$$

With :

m1: Mass flow rate of the 1st stage.

W: Power required in the 1st stage .

h12 : Enthalpy at the delivery point of the 1st stage .

h11 : Enthalpy at the absorption point of the 1st stage .

m1 : Is one of the problem.

$$h_{12} = cp_{12} \cdot T_{12} \dots\dots\dots(III.4)$$

$$h_{11} = cp_{11} \cdot T_{11} \dots\dots\dots(III.5)$$

With :

CP12: Mass heat at constant pressure of the air at discharge.

T12: Temperature of the air at the outlet.

CP11: Mass heat at constant pressure of the air at the inlet of the 1st stage.

T11: Temperature of the air at the inlet of the 1st stage.

For our problem :

T11= -37.2 C° equals 235.8 K

T12 = 120 C° equals 393 K

$$cp_{11} = a_1 + b_1 T_{11} + C_1 T_{11}^2 + d_1 T_{11}^3 \dots\dots\dots(III.6).$$

With :

a1 b1 c1 d1 (specific heat constants).

- a1 = 0.13845 J / Kg. K
- b1= 0.005478 J / Kg. K
- c1 = 0.2923.10-5 J / Kg. K
- d1 =0.6189.10-9 J / Kg. K

$$cp_{12} = a_2 + b_2 T_r + T_r^2 C_2 + d_2 T_r^3 \dots\dots\dots(III.7)$$

With :

a2 b2 c2 d2 (specific heat constants).

- a2 = 0.13845 J / Kg. K
- b2= 0.5478.10-2 J / Kg. K
- c2= -0.02923.10-5 J / Kg. K
- d2=0.6189.10-9 J / Kg. K

we pose :

- a1 = a2
- b1 = b2
- c1 = c2
- d1 = d1

So'

$$h_{11} = cp_{11} \cdot T_{11} \dots\dots\dots(III.8).$$

$$h_{12} = cp_{12} \cdot T_{12} \dots\dots\dots(III.9).$$

So:

the necessary power compression in the first stage:

$$W_1 = m_1 (h_{12} - h_{21})$$

Such that

$$m1=2.0277 \text{ K g/s.}$$

**b) The power required for the compression in the 2nd stage**

$$W_2 = m_2 (h_{22} - h_{21}) \dots\dots\dots(III.10).$$

Such as

$$m2=2.444 \text{ Kgl.}$$

With :

- m2: mass flow in the 2nd stage.
- W2: power required to compress in the 2nd stage.
- h22: Enthalpy at the discharge point.
- h21: Enthalpy at the suction of the 2nd stage.

$$h_{22} = h_{12}$$

.....(III.11).

$$cp_{21} = a_1 + b_1T_{21} + C_1T_{21}^2 + d_1T_{21}^3 \dots\dots\dots(III.12).$$

Avec :

T21 : température d'aspiration de 2éme étage .

T22 : température de refoulemenlde2émeélage .

$$h_{21} = cp_{21} \cdot T_{21} \dots\dots\dots$$

(III.13).

$$cp_{22} = a_1 + b_1T_{22} + C_1T_{22}^2 + d_1T_{22} \dots\dots\dots (III.14).$$

donc :

$$W_2 = m_2 \cdot (h_{22} - h_{21}) \dots\dots\dots (III.15).$$

c) The total power required for the compression in the two stages of the compressor

$$W = W_1 + W_2 \dots\dots\dots(III.16).$$

**III.4.1.2 Polytropic method :**

In the second method of calculation of the power of compression, it is assumed that the operation is reversible poly tropic between the state (A) of outrée, and j'étal (8) of sentie, this following operation:

$$Pv^n = cnst = c' \dots\dots\dots(III.17).$$

With:

C': is the constant of the suction

n: is the coefficient of suction

a) - the compression power :

Poly tropic is given by:

$$W_P = m \left( \frac{n}{n-1} \right) \cdot P_1 \cdot V_1 \left[ \left( \frac{P_2}{P_1} \right) - 1 \right] \dots\dots\dots(III.18).$$

If the operation is deviated from the Poly tropic path for practical reasons, the real compression power is given by:

$$W = \left( \frac{1}{\eta_P} \right) \cdot W_P = \frac{m}{\eta_P} \cdot \frac{n}{n-1} P_1 V_1 \left[ \left( \frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right] \dots\dots(III.19)$$

With :

η\_p: is the poly tropic efficiency ,it, is between 0.7.....0.76

And n =

Instead of using the average value of the coefficient between the state (1) and (2)

For that the power of compression is given by :

$$W = \frac{m}{\eta_P} \cdot \frac{\gamma}{\gamma - 1} P_1 V_1 \left[ \left( \frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \dots\dots\dots(III.20)$$

The strong generally increases this power ,and the mechanical efficiency is covered between 90% and 99% ,and is equal to 97% for compression reasons .

And the required engine power is given by :

$$W_m = \frac{1}{\eta_m} .W \dots\dots\dots(III.21)$$

b)- The power required for actual compression

$$W = \frac{1}{\eta_m} .W_P \dots\dots\dots(III.22)$$

With:

W : Power required at 1st stage .

$W_P$  : the polytropic compression power .

$\eta_p$  : the polytropic suction efficiency .

$\gamma$  :is a given of the problem.

Calculation of the adiabatic suction coefficient

$$\gamma = \frac{c_{P_{11}}}{c_{P_{11}} - R} \dots\dots\dots(III.23)$$

Therefore: n =

Determination of volume :

$$PV = n.R.T \dots\dots\dots(III.24).$$

$$PV = (P/M).R.T \dots\dots\dots(III.25).$$

$$P = (P/M).T = L.r.T \dots\dots\dots(III.26).$$

$$R = 8.341 \text{ J/Kg .K .}$$

With :

$$P = L.r.\left(\frac{1}{V}\right).r.T \dots\dots\dots(III.27).$$

$$V = r.\frac{T}{P} \dots\dots\dots(III.28).$$

V: specific volume m3 / kg

(a) power required for compression in the first stage

$$W_{P1} = m_1 \left( \frac{n}{n-1} \right) \cdot P_1 V_1 \left[ \left( \frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right] \dots\dots\dots(III.29).$$

the power required for actual compression:

$$W_1 = \frac{1}{\eta_P} \cdot W_{P1} \dots\dots\dots(III.30).$$

b) the power required for compression in the 2nd stage:

$$W_{P2} = m_2 \left( \frac{n}{n-1} \right) \cdot P_2 V_2 \left[ \left( \frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right] \dots\dots\dots(III.31).$$

The power required for actual compression :

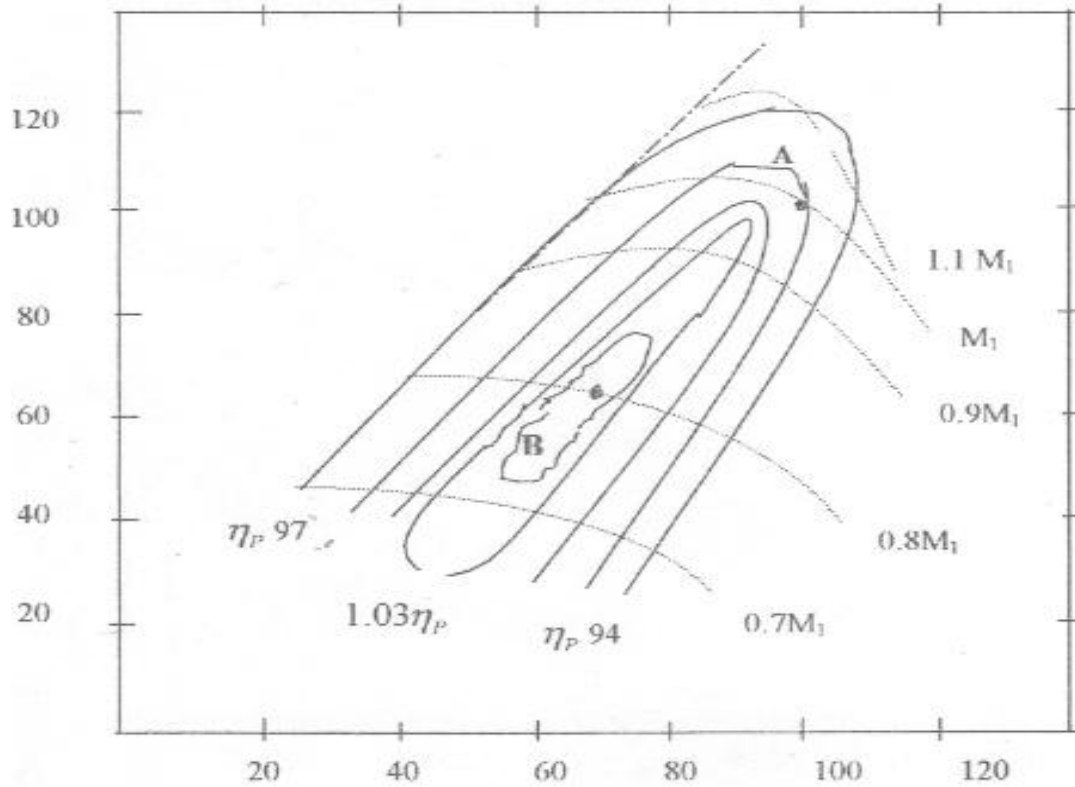
$$W_2 = \frac{1}{\eta_P} \cdot W_{P2} \dots\dots\dots(III.32).$$

(c) The total power required for compression in both stages

$$W' = W_1 + W_2 \dots\dots\dots(III.33)$$

**III 5 Working condition of the centrifugal compressor at various operating conditions**

Figure 4.12 shows the characteristic curves of the centrifugal compressor operation, the horizontal axis shows the percentage of the coefficient of the gas flow rate, this percentage is equal to the real gas flow rate on the one corresponding to the. Optimal operation of the compressor, the vertical axis shows the percentage of the coefficient of the power required for the operation of the compressor in the real conditions of optimal operation.



Figure(4.2): Characteristic curves of centrifugal compressor operation

The coefficient of the flow rate and power are defined by :

$$\theta = \frac{(mv_0)_1}{a_1 D_1^2} \dots\dots\dots(III.34).$$

$$\Omega = \frac{g w_p}{m \cdot a_1^2} \dots\dots\dots(III.35).$$

With :

- a1 : speed of sound at the wheel entrance .
- D1 : diameter of gravity .
- g : acceleration of gravity .
- Wp : power required for a polytropic compression.

The curves representing the variation of the coefficient of the power according to the flow for various speed of rotation.

The good operation of the compressor corresponds to a high efficiency, the left side of the curve represents an unstable operation characterized by vibrations.

Point A represents the optimal state of compressor operation, characterized by flow and power coefficients equal to 100%, and Mach number is equal to M1.

If the working conditions change, the compressor operation follows the curves shown in this figure (3.2).

To save energy, point B is recommended for operation at maximum power, at this point the Mach number is 70% of its reference value  $M_1$  with a flow coefficient equal to 60% of the reference value, and a power coefficient equal to 67% of the reference value  $\Omega$ .

The two figures (3.1) and (3.2) show that there is a linear dependency between the suction flow rate of the first stage and that of the second stage. 3) and (3.4) show the inverse proportional relationship between the total power of the compressor and the discharge temperature. If the temperature at this point decreases, the pressure will also decrease, which, from a purely practical point of view, leads to a phenomenon known as surge.

The application of the methods of calculation of the power (polytropic, isentropic) allows us to draw the following graphs:

**Conclusion:**

In this chapter, we discuss in relation to compressor dynamics the suitability of a scroll machine for small-sized refrigerant compressors. For this purpose the calculated results on the crankshaft load fluctuation, the crankshaft rotary behavior, the unbalanced inertia forces, the compressor vibrations and the mechanical efficiency of a scroll-type compressor are presented initially. Secondly, the calculated results are compared with those of four different types of compressors: an one-rolling-piston rotary type, a two-rolling-pistons two-blades rotary type, an one-rolling-piston two-blades rotary type and a single-cylinder reciprocating type

**CHAPTER 4**  
**DEVELOPMENT STUDY OF A SYSTEM**  
**FOR ON-LINE COMPRESSOR**  
**MONITORING**

## IV.1 Introduction

The monitoring systems in the oil industries have a great importance in the production chain and its continuity.

A good monitoring system in addition to its reliability in measuring the various operating parameters of the devices to be monitored is known by its ability to detect anomalies and failures which is subsequently minimizes the time and cost of repair and maintenance.

In the HBK gas processing center, the control system in the entire process is the Di-Tronic2. Despite its reliability in measurement, it cannot diagnose individual machines and devices. In case of malfunctions, this system is suitable to trigger an alarm or to stop the device completely. In this case, the mechanical maintenance department intervenes to repair the machine (displacement, dismantling, analysis, solution and reassembly), which can sometimes take days.

## IV.2 Objective

Our objective is to propose and implement in Matlab an approach for the development of a system for the on-line monitoring of the compressor, using artificial neural networks of the multi-layer perceptron type (MLP). The goal of our work is to propose rectifications to the Di-Tronics2 system so that it is able to accurately specify the type of failure that can occur on this compressor.

The operating parameters of the compressor (suction pressure, inlet temperature, suction flow, compressor power, rotor speed) The operating parameters of the compressor (suction pressure, inlet temperature, suction flow rate, compressor power, rotor speed, etc.), the two components of radial and axial vibration of the two ends of the rotor, as well as the compression ratio and the number of stages, are exploited and used as input data in order to feed an MLP neural network using the error gradient back propagation algorithm with momentum .

The diagram below (Figure 4.1) illustrates the proposed compressor monitoring system.

## IV.3. The biological neuron

The biological neuron is a living cell specialized in electrical signal processing.

Neurons are connected to each other by links called axons. These axons will themselves play an important role in the logical behavior of the whole. These axons conduct electrical signals from the output of one neuron to the input (synapse) of another neuron.

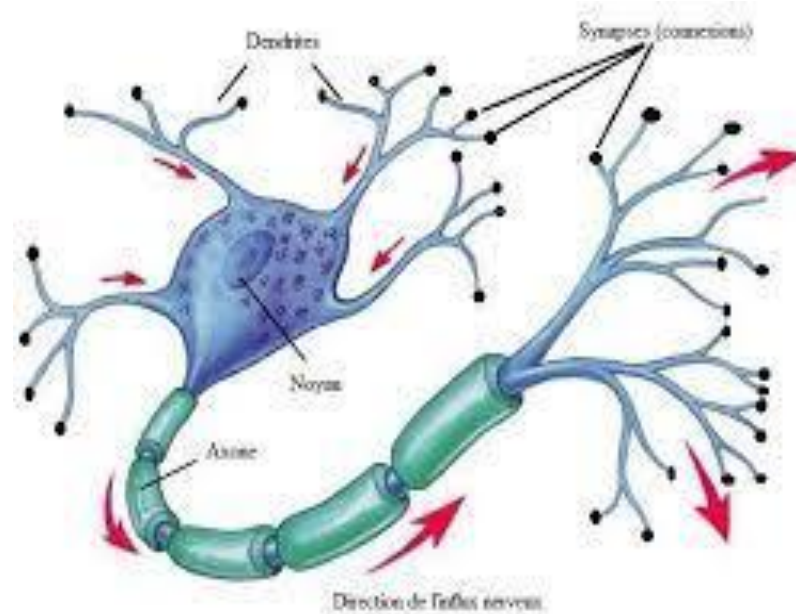
The neurons make a summation of the signals received in input and according to the result obtained will provide a current in output. (figure 4.1)

The structure of a neuron is composed of three parts:

The summa: or nerve activity cell, at the center of the neuron.

The axon: attached to the somma, which is electrically active, it conducts the impulse led by the neuron.

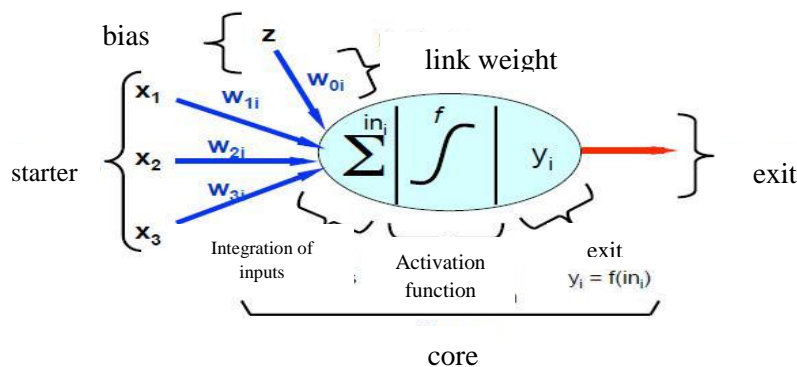
Dendrites: electrically passive, they receive impulses from other neurons.



**Figure (4.3): The biological neuron**

### IV.3.1. Formal neuron

The diagram shows the composition of an artificial neuron. Each neuron in the network is an elementary machine. It receives a number of input variables from upstream neurons. To each of these inputs is associated a weight that represents the strength of the connection between the two neurons. Each neuron has a single output which then branches out to represent inputs that will feed other neurons downstream. To summarize, each neuron computes a single output based on the information it is given.



The neuron as an elementary unit acts in the following way:

1st phase: The neuron computes the weighted sum of the inputs (based on the strength of the connections). As the learning has been done before, the weight of the connections is already determined and fixed.

2nd phase : From the obtained value, an activation or transfer function will calculate the value of the neuron state. The neuron compares the weighted sum of the inputs to a threshold value and then provides an output response.

Most functions are continuous and therefore offer an infinite number of possible values in the intervals  $[0 ; +1]$  or  $[-1 ; +1]$ . There are different types of transfer functions for the artificial neuron:

- threshold function
- piecewise linear function
- sigmoid function
- Gaussian function

### IV.3.2 Modeling a formal (artificial) neuron

The modeling consists in implementing a neural network system under an artificial aspect, not a biological one, it supposes that according to the biological principle we will have a correspondence for each element composing the biological neuron, thus a modeling for each of them. We can summarize this modeling in table 4.1, which will allow us to clearly see the transition between the biological neuron and the formal neuron.

**Table (4.1) Analogy between the biological neuron and the formal neuron**

Artificial neuron	Biological neuron
Weight	of connections Synapses
Output	signal Axons
Input	signal Dendrite
Activation	function Somma

1) Entries: Can be

Boolean.

Binary (0, 1) or bipolar (-1, 1).

Real.

2) Activation function

This function allows to define the internal state of the neuron according to its total input, let us quote as an example some functions often used:

2.a) Binary function with threshold : for example

- Heaviside function defined by

The threshold introduces a non-linearity in the behavior of the neuron, however it limits the range of possible responses to two values.

2.b) Linear function

This is one of the simplest activation functions, its function is defined by :

$$F(x) = x$$

2.d) Sigmoid function

It is the continuous equivalent of the linear function. Being continuous, it is derivable, especially since its derivative is simple to calculate,

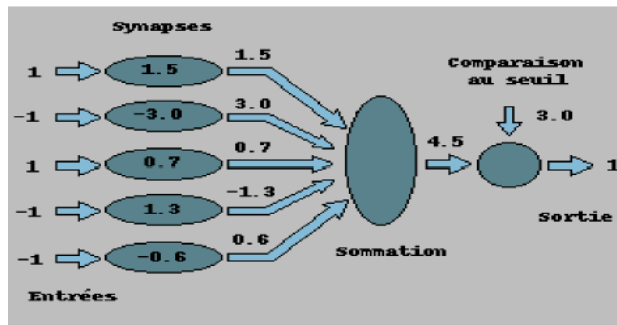
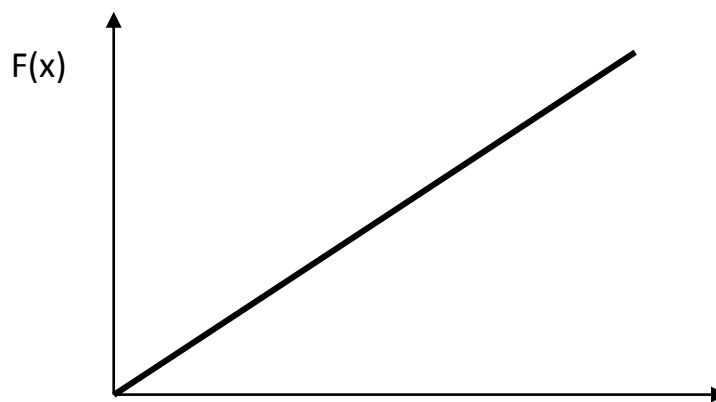


Figure (4.4): Fonction sigmoïde



3) Output function

It calculates the output of a neuron according to its activation state. In general, this function is considered as the identity function. It can be :

$$f(x) = \frac{1}{1 + e^{-x}}$$

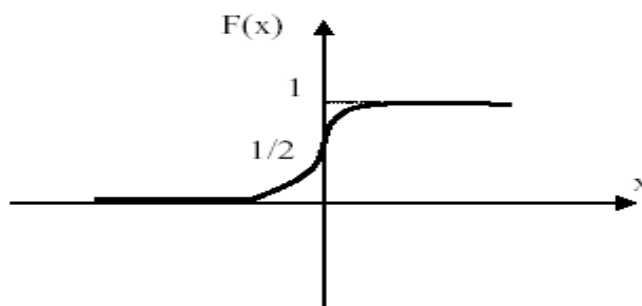


Figure (4.4): Fonction sigmoïde

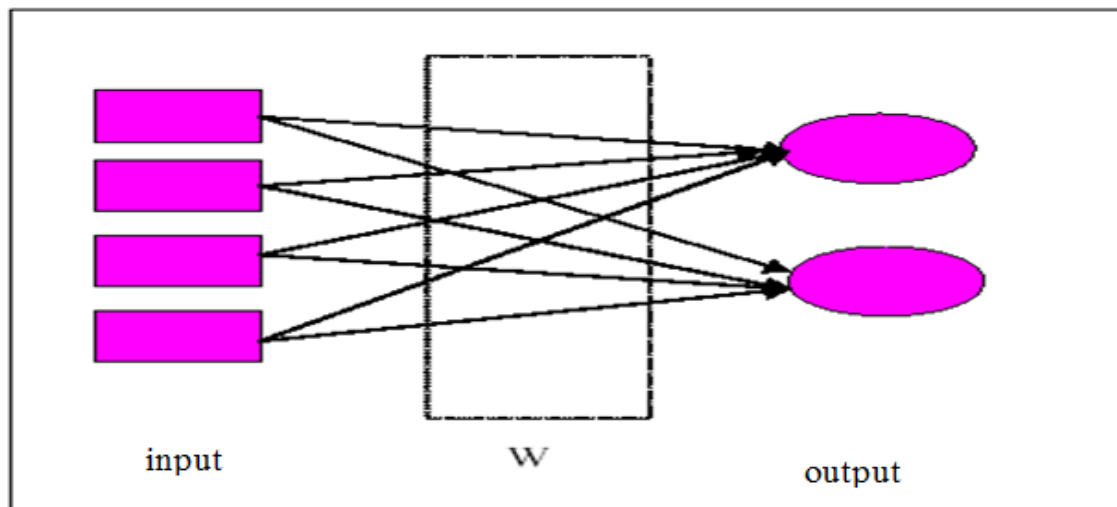
Binary (0, 1) or bipolar (-1, 1) Real.

#### IV.3.2.1 Network architecture

The connections between the neurons that compose the network describe the topology of the model. It can be any topology, but most of the time it is possible to distinguish a certain regularity (full connection network).

#### IV.3.2.2 Single layer network

The structure of a monolayer network is such that neurons organized in input are fully connected to other neurons organized in output by a modifiable layer of weights (figure 4.8)



#### IV.3.2.3 Multi-layer network

The neurons are arranged by layer. There are no connections between neurons of the same layer, and connections are only made with neurons of downstream layers. Usually, each neuron of a layer is connected to all neurons of the next layer and this one only. This allows us to introduce the notion of direction of information flow (of activation) within a network and thus define the concepts of input neuron, output neuron. By extension, we call input layer the set of input neurons, output layer the set of output neurons. The intermediate layers having no contact with the outside are called hidden layers. (figure 4.9).

#### IV.3.2.4 Fully connected network

This is the most general interconnection structure. Each neuron is connected to all the neurons of the network (and to itself).

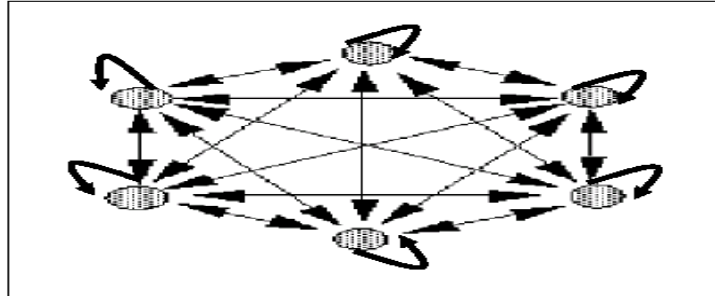


Figure (4.5) : Fully connected network

#### IV.3.2.3 The perceptron model

The perceptron mechanism was invented by the psychologist FRANK Rosenblat in the late 1950s. It represented his attempt to illustrate some fundamental properties of intelligent systems in general.

The network in this model is made up of three layers: An input layer (the retina), providing data to an intermediate layer (hidden layer), in charge of the calculations, that is providing the sum of the impulses that come to it from the cells to which it is connected, and it generally responds according to a defined law with a threshold, itself connected to the output layer (decision layer), representing the examples to be memorized. Only this last layer sends signals back to the intermediate layer, until their connections stabilize (figure 4.11).

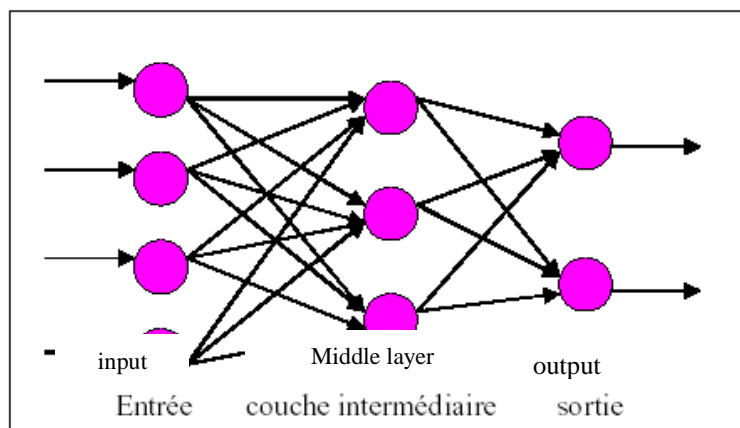


Figure (4.6) : The perceptron model

#### **IV.4. General architecture of the implemented monitoring concept:**

This system has two main phases: the first phase is the data acquisition phase, it acquires data from the compressor. These data are in the form of signals, measured during the operation of the compressor. While the second phase "decision phase" is processed at the level of neural networks.

We propose in the following to develop in detail these two phases which constitute our monitoring system.

##### **IV.4.1. Phase I: Data acquisition**

The compressor, like all the machines of the unit, contains sensitive probes to measure the various quantities of which here are some data:

temperature sensors or thermocouples

Pressure sensors (suction and discharge)

axial and radial proximity sensors (rotor vibration sensors)

These sensors are transmitted from the compressor to the control room by special cables.

The acquisition card installed on the PC has the role of translating these signals into displayable values.

All the data of this work are then real data taken from the control room.

##### **IV.4.2. Phase II: Implementation of a neural network model**

This phase is the decision stage. Through the result obtained by the network, we will determine the state of the compressor, namely :

Discharge pressure within the norms: normal operation of the compressor;

Discharge pressure outside the norms: abnormal operation (triggering of an alarm, diagnosis of the problem encountered, shutdown, etc.)

The monitoring of our compressor by neural networks involves three major steps:

The learning of the neural network, in order to learn the process (gas compression) by the coupling (association) of the desired inputs and outputs.

This step does not exclude the choice of parameters for the neural network itself.

Choosing these parameters properly allows the network to converge quickly (minimal learning time) and to have a good estimate of the pressure delivered by the compressor.

Testing the neural network (evaluation) in order to estimate the accuracy of the proposed model for events that were not presented during the learning phase.

Implementing the network for on-line monitoring of the compression process (prediction of the discharge pressure).

###### **IV.4.2.1. Type of neural network model proposed**

The neural network to be studied is a multi-layer feed-forward network, comprising an input layer, a hidden layer and an output layer. The choice of this type of architecture (3 layers) is arbitrary, the hidden layer is used to extract more information from the input data of the network. Moreover, the use of this layer allows to give a non-linear form between the input and output models. On the other hand, the MLP (Multi Layer Perceptron) type of neural network with gradient back-propagation was chosen for its simplicity, its very wide use in

online supervision systems of compression processes and for the satisfactory results obtained with this model.

#### IV.4.2.2. Input data of the network

The tabl -----(4.1)

Les tabl-----normalisé

#### IV.4.2.3. Training of the network:

Gradient back-propagation algorithm with momentum

The algorithm used for training the neural network is the error gradient backpropagation algorithm with an additional term called "momentum"

Part I Configuration and Programming of a multilayer neural network

The fundamental principle of the chosen neural network is the following: the network is "trained" to associate an input model "input vector" to an output model "output vector". During the learning phase, the two input and output models are presented to the neural network in order to allow it to learn and memorize the shape of these two vectors.

The main learning steps of the proposed neural network for our monitoring system design shown in Figure 4.3 are:

Step 1: Initialization of the weights

The initialization of the weights is done in a random way, they are initialized randomly but in a predefined interval, the values of the weights and the biases are included between  $[-1, +1]$ . This technique is used to allow a fast convergence to the network. Let therefore :  $w_{1ij}, j = 1, 2, \dots, l$  and  $i = 1, 2, \dots, 12$

Where the upper index (1) means that it is the weight matrix of the input layer, the index (j) means the arrival (index of the neuron in the hidden layer). In our case, it varies from 1 to l, number of neurons in the hidden layer, the index (i) indicates the starting layer, it varies from 1 to 12, number of neurons in the input layer.

$w_{2kj}, k=1, j = 1, 2, \dots, l$

Where the upper index (2) means that it is the weight matrix of the hidden layer, (k) is the index corresponding to the number of neurons in the output layer, it is equal to 1 (one output), (j) is the index corresponding to the number of neurons in the hidden layer.

$b_{1j} j = 1, 2, \dots, l$  and  $b_{2k}, k = 1$ , are the values of the biases corresponding to the hidden and output layers respectively. Their values are equal to unity (1).

Step 2: Reading the input vector and the desired output

The input vector consists of the suction pressure  $P_1$ , the intake temperature  $T_1$ , the suction flow  $Q_{asp}$ , the compressor power, the rotor speed  $V_r$ , the number of stages  $N_{and}$ , the compression ratio  $\tau_c$ , the two vibration components of the rotor near suction (axial and radial)  $(D_x, D_y)$  and the two vibration components of the rotor near discharge (axial and radial)  $(F_x, F_y)$  as well as the axial vibration of the rotor  $(D_{ax})$

The measured pressure value  $P_2$  represents the desired network output (or target).

Step 3: Normalization of the input vector

During the learning phase of the network, the values of the input vector must be normalized in the interval  $[0.1, 0.9]$  in order to allow an efficient processing by the network. The function (linear function) used for the normalization of the input vector is given by the following relation:

$$X_N = (X - X_{min}) \frac{(X_{Nmax} - X_{Nmin})}{(X_{max} - X_{min})} + X_{Nmin}$$

Where:

XN: Normalized value corresponding to the elements of the input vector  
( P1,T1,Qasp,...etc),

X: Real value of an element of the input vector,

Xmin : Minimum value of an element of the input vector,

Xmax: Maximum value of an element of the input vector,

XNmin: Minimum value of the normalization vector [0.1, 0.9] equal to 0.1,

XNmax : Maximum value of the normalization vector [0.1, 0.9] equal to 0.9.

The network will be fed after having normalized the elements of the input vector to associate them with the desired outputs.

**Step 4:** Forward or "feed-forward" propagation

As the network is organized in successive layers, the neurons of one layer are linked to those of another (following) layer as shown in figure III.4. The calculation of each output is done in a forward direction, i.e. from the input layer to the hidden layer and then from the hidden layer to the output layer.

- The output of each input neuron simply takes the values of the input vector (input patterns).

$y_{i0}$  : output of the input layer (layer 0),

$y_{10}=P1, y_{20}=T1, \dots, y_{120}=Fy$

- The calculation of the output of the input layer to the hidden layer and the output of the hidden layer to the output layer is done according to relation III.2 :

$y_{j1}(j= 1,2,\dots,l) =$  : output of the hidden layer (layer 1)

$y_{k2}$  : output of the last layer (layer 2), it expresses the value of the predicted pressure P2.

The input of the hidden layer is given by :

$$hj1 = w_{j1}T1 + w_{j2}P1 + w_{j3}Qasp + \dots + w_{j12}Fy$$

or else :

$$hj1 = w_{j1}y_{10} + w_{j2}y_{20} + w_{j3}y_{30} + \dots + w_{j12}y_{120}$$

Which is written:

$$h_j^1 = \sum_{i=1}^n w_{ji}^1 y_i^0 + b_j^1, j = (1,2, \dots, l); n = 12$$

The output of this hidden layer is given by :

$$y_j^1 = f(h_j^1); j = (1,2, \dots, l)$$

Where  $f(\cdot)$  is the activation function. It is a sigmoid function of logistic type, which is :

$$f(som) = \frac{1}{1 + \exp(-som)}$$

The variable som being the sum :

$$som_j = \sum_{i=1}^n w_{ji}^1 x_i + b_j^1, j = (1,2, \dots, l); n = 12$$

The input of the output layer (last layer) is expressed by:

$$h_k^2 = w_{k1}y_1^1 + w_{k2}y_2^1 + \dots + w_{k12}y_{12}^1$$

The output of this last layer is written as follows:

$$y_k^2 = f(h_k^2); k = 1$$

**Step 5:** Error calculation

The error in a given layer is expressed by the relation noted :  
the error on the output layer is :

$$\delta_k^2 = (d - y_k^2) f'(h_k^2); k = 1$$

the error on the hidden layer is :

$$\delta_j^1 = \left( \sum_{k=1}^m \delta_k^2 w_{kj}^2 \right) f'(h_j^1); m = 1$$

Where n is the number of inputs presented to the network, m is the number of neurons in the output layer (which is equal to 1), d is the desired output (measured pressure values), and y is the output calculated by the network.

Step 6 : Adaptation of the network and calculation of the outputs

This step consists in adapting the weights and biases of the different interconnections of the network (update of the weight matrix  $w_{ji}$  and the bias vector  $b_j$ ).

The update is done following the error gradient backpropagation algorithm (figure III.3) with an additional term: "momentum". The error is thus back-propagated through the network by a quantity  $\Delta w$  and  $\Delta b$

$$\begin{cases} (\Delta w_{kj}^2)_{nouveau} = \eta \delta_k^2 y_j^1 + \alpha (\Delta w_{kj}^2)_{ancien} \\ (\Delta w_{j1}^1)_{nouveau} = \eta \delta_j^1 y_i^0 + \alpha (\Delta w_{j1}^1)_{ancien} \\ (\Delta b_k^2)_{nouveau} = \eta \delta_k^2 + \alpha (\Delta b_k^2)_{ancien} \\ (\Delta b_j^1)_{nouveau} = \eta \delta_j^1 + \alpha (\Delta b_j^1)_{ancien} \end{cases} \quad \text{and} \quad \begin{cases} i = 1, 2, \dots, 12 \\ j = 1, 2, \dots, l \\ k = 1 \end{cases}$$

The weights and biases are incremented according to the relation :

$$\Delta w_{ji}(I) = \eta \frac{\partial e_k}{\partial w_{ki}} + \alpha \Delta w_{ji}(I - 1)$$

This gives:

$$\begin{cases} w_{ji}^1 = w_{ji}^1 + \Delta w_{ji}^1 \\ w_{kj}^2 = w_{kj}^2 + \Delta w_{kj}^2 \\ b_j^1 = b_j^1 + \Delta b_j^1 \\ b_k^2 = b_k^2 + \Delta b_k^2 \end{cases} \quad \text{with} \quad \begin{cases} i = 1, 2, \dots, 12 \\ j = 1, 2, \dots, l \\ k = 1 \end{cases}$$

Where is a parameter specific to the neural network called "learning rate" and is a factor called "momentum". This parameter allows to take into account the evolution of the learning over time. In other words, it allows to weight the influence of the previous variation on the current variation (we are talking here about the variation or update of weights and biases).

Step 7: Calculation of the MSE error

In this step we calculate the root mean square error MSE (also called network performance). We try to get as close as possible to an imposed tolerance for a given number of iterations. The control of these two factors (tolerance and number of iterations) ensures, with the right choice of the two parameters, the fast and precise convergence towards the target value (predicted P2)

$$MSE = \frac{1}{2} \sum (d - y_i^2)^2$$

The gradient backpropagation algorithm continues to be run for a predefined number of iterations until an acceptable error is reached through the learning process. Once the update quantities of weights and biases are computed, we again compute the outputs of the network (forward propagation) following the relationships presented earlier in step 4.

In multilayer neural networks, a large number of iterations is required to satisfy the imposed error. This is in order to have a high degree of reliability of such a monitoring system.

## IV.5 Approach adopted for the choice of an optimal neural network

### IV.5.1 Preliminaries

Our strategy consists in implementing a neural network with different numbers of neurons in the hidden layer (variable number of hidden neurons), and thus several architectures with the aim of optimizing on these different architectures.

The general architecture of the network is "12-i-1" (figure 4.3) with  $i=1,2,\dots,30$  (number of hidden neurons). We then choose the optimal architecture that gives an acceptable test error compared to the one imposed for a given number of iterations. Both parameters (learning rate and momentum respectively) were chosen as constant (fixed), and these values were chosen randomly. If the choice of an optimal architecture is not made, we will make an optimization on the two parameters of the network, namely, and which have an influence on it, by fixing one and varying the other and vice versa.

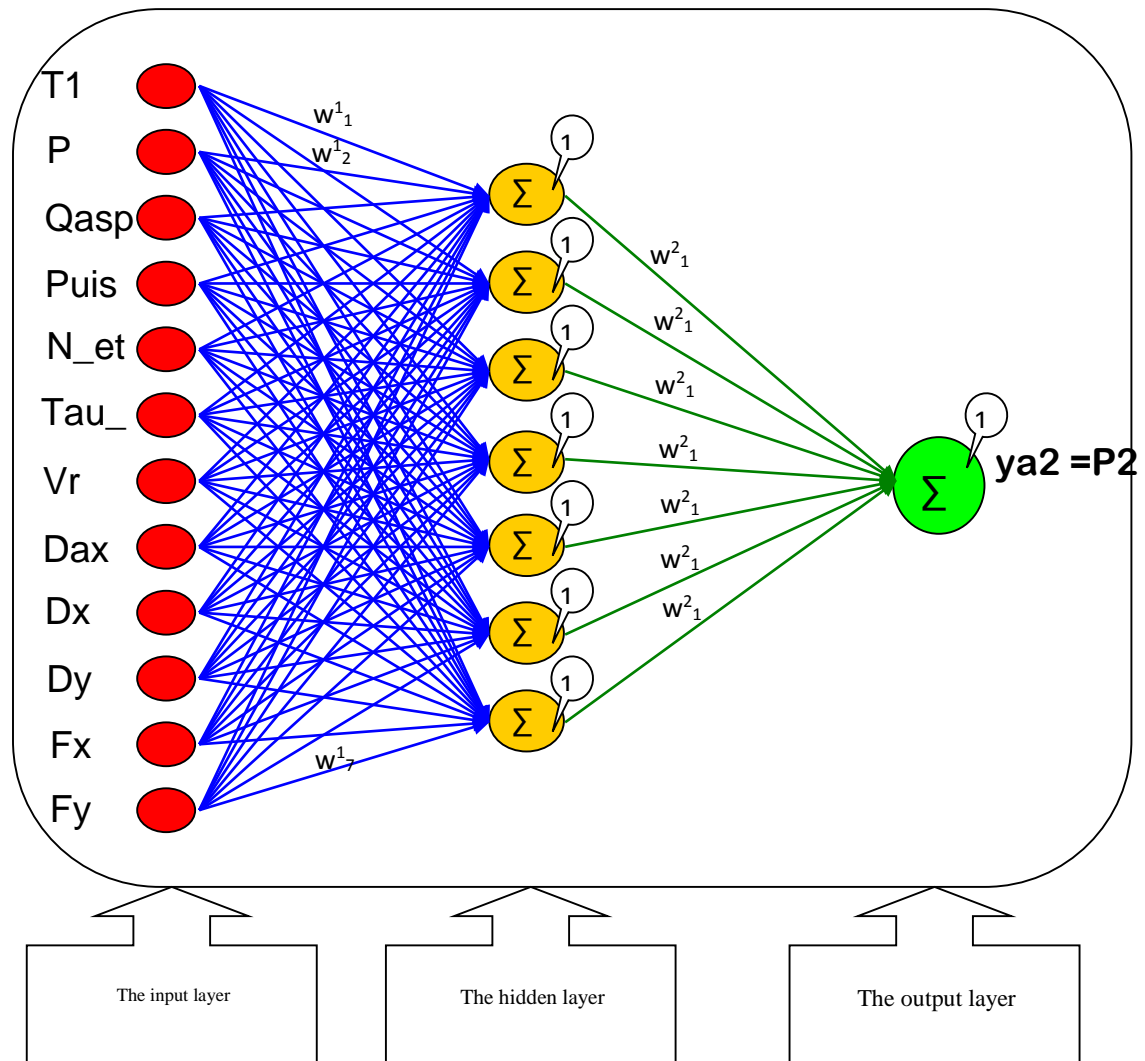
Our network is thus parameterized as follows:

The weights are initialized between -1 and +1. The cost function used for the different architectures is the mean square error MSE. We opted for a test error  $MSET=5E-09$ , and a number of iterations  $NB=10000$  iterations, the activation function in the hidden layer is a sigmoid function of logistic type:

$$f(x) = \frac{1}{1+\exp(-x)}$$

In order to limit the output amplitude between 0 and 1 and a linear function in the output layer  $f(\text{som}) = \text{som}$ .

We used the combination of learning/testing, (30/13). There are no general rules for the choice of the combination of the database (learning/testing), so the right choice is the one corresponding to the smallest value of the MSET error by doing several trials



## IV.5.2. General structure of the developed algorithm

The proposed algorithm (figure 4.6) is composed of two essential parts, the first one consists in learning the network by associating the 30 input/output examples, the second one is interested in testing it by using examples (4,3 examples) other than those used for learning. We note that a neural network is considered as "good" when it generalizes well, i.e. it must have a strong generalization power, i.e. when we go to the test phase, the error must be acceptable with a good success rate. The values used for the test are different from those presented to the network for the learning phase in order to verify the generalization power.

## IV.5.3 Determination of the neural network configuration

### IV.5.3.1 Choice of an optimal architecture

Different architectures (30 architectures in total) have been studied in order to choose the architecture for which the test error is the lowest (acceptable error with respect to the fixed tolerance). As the number of neurons in the hidden layer varies, each architecture was trained for random weights and biases (different initialization values), the weights obtained after the training phase were used to test the network. The minimum error of the whole testing process of these different architectures will be used as a criterion to choose a first optimization. The results obtained are summarized in Table IV.3.

**Table (4.3): Choice of the right architecture**

Nbr_Neur	MSEA	MSET
12-01-1	2.77E-17	4.21E-14
12-02-1	6.08E-17	4.22E-09
12-03-1	8.81E-18	3.41E-08
12-04-1	1.26E-17	1.33E-08
12-05-1	2.37E-16	7.25E-15
12-06-1	3.21E-17	3.25E-10
12-07-1	2.96E-18	5.32E-16
12-08-1	1.14E-17	3.98E-14
12-09-1	2.47E-16	5.16E-12
12-10-1	3.02E-17	1.78E-15
12-11-1	2.11E-16	5.93E-15
12-12-1	3.10E-16	8.29E-15

According to the results in table (4.3), the analysis of the different architectures based on the root mean square errors allowed us to observe several phenomena. These phenomena are mainly due to the nature of the neural networks themselves, the errors vary randomly with the different architectures.

The learning errors varied between a minimum of  $2.96E-18$  and a maximum of  $3.50E-15$ , while the test errors had a minimum of  $5.32E-16$  and a maximum of  $4.21E-14$ .

The minimum test error  $MSET = 5.32E-16$  corresponds to the 12-07-1 architecture.

The learning error  $MSEA$  and the test error  $MSET$  are plotted in Figures 4.9, 4.10 as a function of the number of neurons in the hidden layer.

## IV.6 Simulation of Thermal Parameters and Optimization of the Monitoring System Using ANR for the Compressor

Table (4.4): value of the predicted discharge pressure Pref\_p and absolute errors for

the learning phase with the 12-7-1 architecture Ir=0.5 and mc=0.7

No. Pref Example ((bar	Pref_m_measured normalized (bar)	Pref_p_normalized (bar)	Absolute (Error( $\Delta P_2$ Pref_p-Pref_m) ) ((bar
01	1.00E-01	1.0006e-001	5.8830e-005
02	1.00E-01	1.0013e-001	1.3441e-004
03	1.00E-01	1.0006e-001	6.1065e-005
04	1.00E-01	9.9982e-002	1.7606e-005
05	1.00E-01	1.0011e-001	1.0603e-004
06	1.00E-01	9.9997e-002	2.9416e-006
07	1.00E-01	1.0014e-001	1.4374e-004
08	1.00E-01	9.9982e-002	1.8229e-005
09	1.00E-01	1.0001e-001	6.2357e-006
10	1.00E-01	9.9995e-002	5.1448e-006
11	1.00E-01	1.0001e-001	1.1491e-005
12	1.00E-01	9.9985e-002	1.5095e-005
13	1.00E-01	9.9979e-002	2.0927e-005
14	1.00E-01	9.9971e-002	2.9165e-005
15	1.00E-01	1.0003e-001	2.9714e-005
16	1.00E-01	1.0011e-001	1.0972e-004
17	1.00E-01	9.9966e-002	3.3954e-005
18	1.00E-01	1.0004e-001	3.6778e-005
19	1.00E-01	9.9969e-002	3.1355e-005
20	1.00E-01	1.0001e-001	1.0324e-005
21	1.00E-01	1.0002e-001	2.0167e-005
22	1.00E-01	1.0002e-001	2.0506e-005
23	1.00E-01	1.0009e-001	8.7617e-005
24	1.00E-01	1.0010e-001	9.7300e-005
25	1.00E-01	9.9979e-002	2.0522e-005
26	1.00E-01	9.9996e-002	4.0624e-006
27	1.00E-01	9.9965e-002	3.4734e-005
28	1.00E-01	1.0021e-001	2.1141e-004
29	1.00E-01	9.9983e-002	1.7442e-005
30	1.00E-01	1.0003e-001	3.4825e-005

**Table (4.5): value of the predicted discharge pressure Pref and absolute errors for the TEST phase with the 12-7-1 architecture Ir=0.5 and mc=0.7**

N°	Pref Exemple (bar)	Pref_m_mesurée normalisée(bar)	Pref_p_prédite normalisée(bar)	Erreur Absolue( $\Delta P_2$ ) (Pref_p-Pref_m) (bar)
1		1.00E-01	1.0007e-001	6.5535e-005
2		1.00E-01	1.0016e-001	1.5668e-004
3		1.00E-01	1.0008e-001	7.5414e-005
4		1.00E-01	9.9964e-002	3.6438e-005
5		1.00E-01	1.0013e-001	1.2707e-004
6		1.00E-01	9.9983e-002	1.6977e-005
7		1.00E-01	1.0017e-001	1.6575e-004
8		1.00E-01	9.9964e-002	3.6429e-005
9		1.00E-01	9.9998e-002	1.9443e-006
10		1.00E-01	9.9980e-002	2.0177e-005
11		1.00E-01	1.0000e-001	1.2185e-006
12		1.00E-01	9.9965e-002	3.4961e-005
13		1.00E-01	9.9961e-002	3.8863e-005

The application of the method of calculation of the predicted discharge pressure and the absolute errors for the TEST phase, allowed us to draw the following graphs:

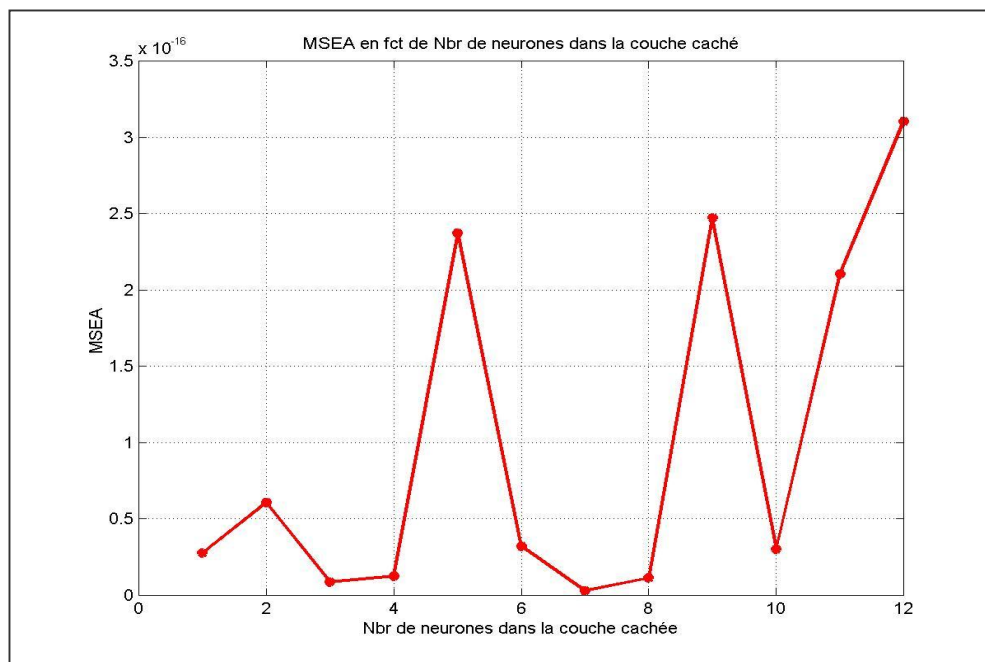
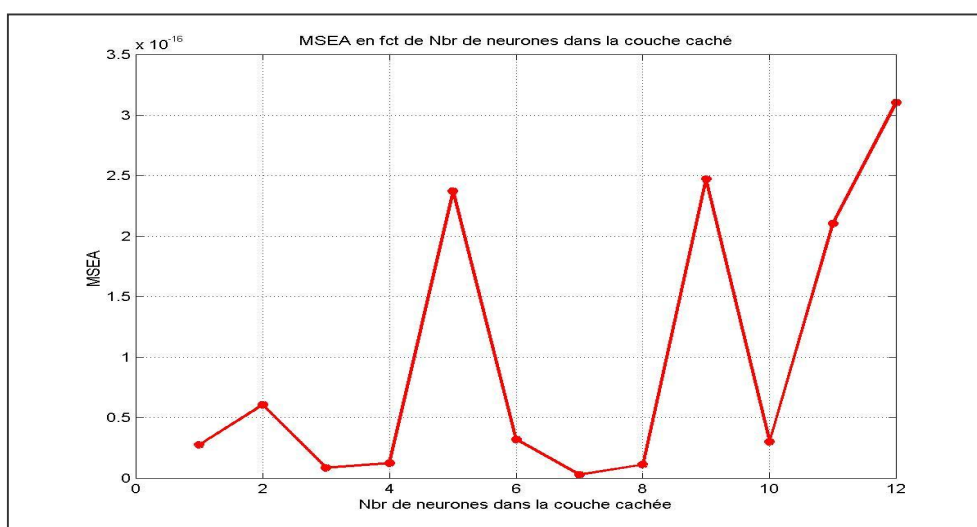
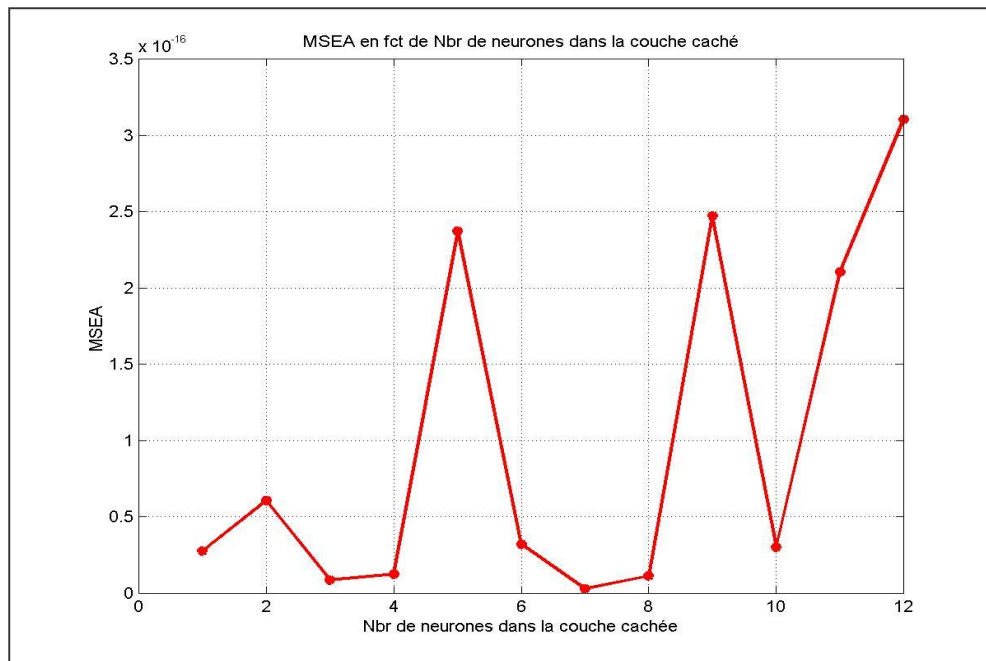
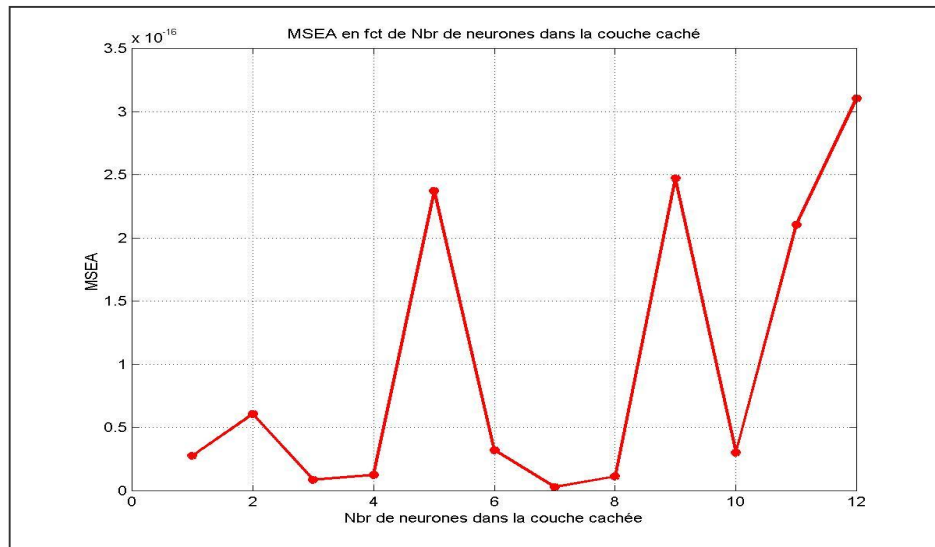
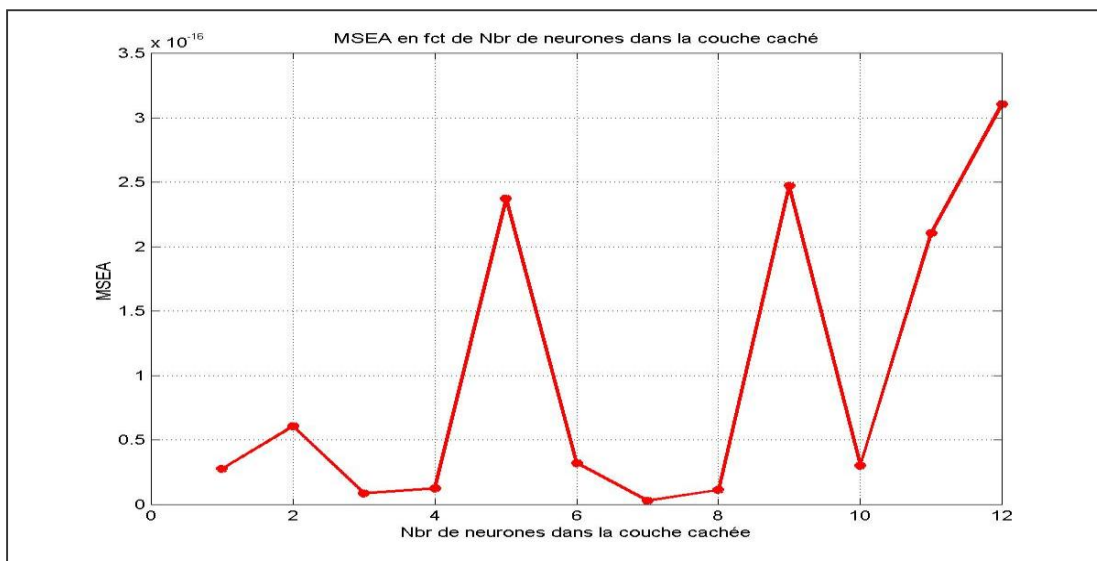
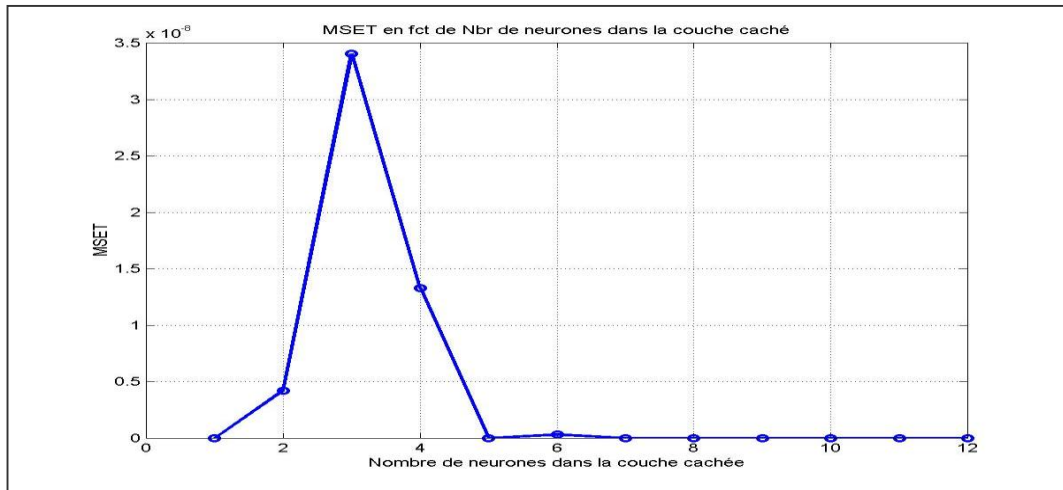


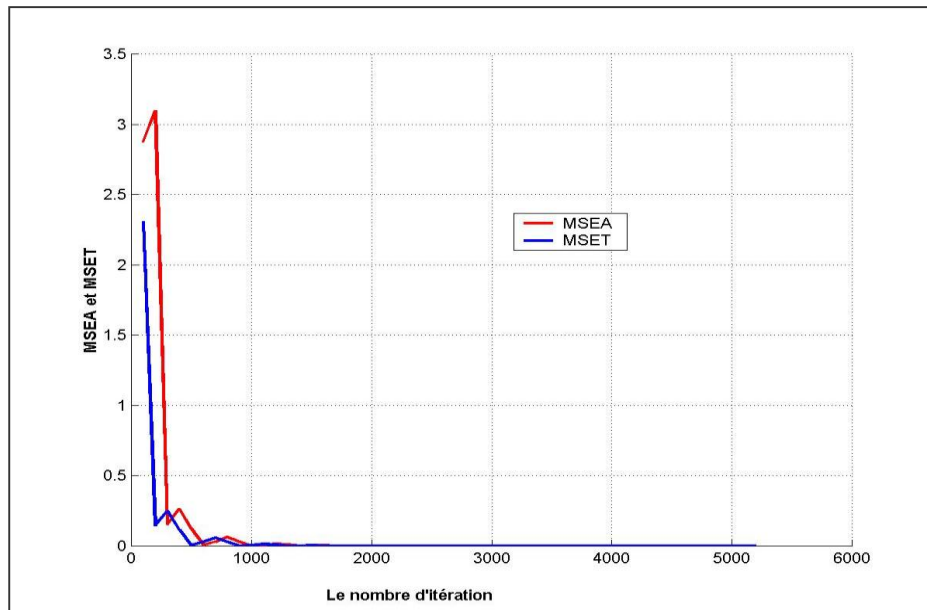
Figure 4.7 : MSEA as a function of Number of neurons in the hidden layer





**Figure (4.8): MSEA and MSET as a function of Number of neurons in the hidden layer**

Figure 4.9: Root mean square error as a function of the number of iterations



In order to quantify the quality of the predictions, and thus the success rate of the designed network, in addition to the root mean square error MSE (network performance), different statistical evaluations (errors) have been used, the root mean square RMS of the error between the measured value and the predicted value of the wear is calculated by using the following relationship:

Where  $N$  is the number of predictions.

A success rate of 97.31% (RMS Error =  $2.6848e-002$ ), and an  $R$  ratio = 0.99749 for the training was obtained. While for the test, the success rate was 92.83% (RMS Error =  $7.1707e-002$ ), and the ratio was  $R = 0.99635$ .

We clearly notice that this ratio approaches unity and that the success rate for the test reached a very satisfactory percentage, which reflects the performance of our network.

To show the correlation between the measured wear  $VB_m$  and the predicted wear  $VB_p$  of the two learning and testing phases (normalized values), we have plotted these in Figures 4.14 and 4.15 respectively.

Problems that hinder the efficiency of the productive tool.

## IV.7 Conclusion

In our chapter, we plan to develop and optimize a configuration of a cutting tool wear monitoring system, adapted to turning operations, and based on an optimized neural network, fed with data from cutting force signals.

To this end, we have organized the work into three parts:

In the first part we present a detailed state of the art on the methods of detection of the wear of the cutting tools, namely the methods based on the measurement of the cutting force, the acoustic emission, the vibrations, the temperature (indirect methods) and other less used methods (direct methods) then some notions on the fusion of probes.

The second part entitled "online monitoring of cutting tools based on neural networks" is devoted to the concept of monitoring system, the automatic monitoring of the wear of cutting tools, the application of neural networks in the development of such systems, the signal processing and finally the various architectures of neural networks most frequently used in this field.

The third and last part is dedicated to the development of a methodological approach for the optimization of a neural network configuration, adapted to the automatic monitoring of cutting tool wear. It includes several chapters, from the general architecture to the presentation of the two phases of the system developed by developing the error gradient backpropagation algorithm, used for the training of a neural network of MLP (Multi Layer Perceptron) type, and by studying several parameters in order to improve the latter.

# **General Conclusion**

## General Conclusion

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The study presented in this thesis allows us to note that preventive maintenance plays a primordial role to ensure a good functioning and an excellent efficiency of the centrifugal compressor. Object of our study. As it is known, this type of maintenance is used to predict the type of problems before they occur, which is a very useful way to increase the life of our devices

The careful examination of the history of our centrifugal compressor, has allowed us to notice clearly that among the problems that risk to reduce enormously the efficiency and the good functioning of the compressor, the phenomena of the wear and the vibration the cause of this problem are diverse; such as the bad lubrication of the mobile parts, the incompatibility between the speed that gives the electric motor and the one of the shaft of the compressor

We can classify following this descriptive study the causes of vibration and wear, in physical causes keeping the sudden increase of the pressure within the compressor.

A general conclusion and perspectives of improvement of this present work  
By end this dissertation.

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## Summary

In this thesis we have found that preventive maintenance plays a key role in ensuring proper operation and excellent efficiency of the centrifugal compressor. Object of our study. As it is known, this type of maintenance serves to predict the type of problems before they occur, which offers a very useful way to increase the life of our compressors.

Our objective is to propose and implement in Matlab an approach for the development of a system for the on-line monitoring of the compressor, using artificial neural networks of the multi-layer perceptron (MLP) type. The aim of our work is to propose rectifications on the Di-Tronics2 system so that it is able to specify with accuracy the type of failure that can occur on this compressor.

Key words: compressor, maintenance, centrifugal compressor.

ملخص :

في هذه الأطروحة وجدنا أن الصيانة الوقائية تلعب دورًا رئيسيًا في ضمان التشغيل السليم والكفاءة الممتازة لضغط الطرد المركزي الذي هو موضوع دراستنا.

كما هو معروف ، يعمل هذا النوع من الصيانة على التنبؤ بنوع المشكلات قبل حدوثها ، مما يوفر طريقة مفيدة للغاية لزيادة عمر الضواغط.

هدفنا هو اقتراح وتنفيذ نهج في Matlab لتطوير نظام للمراقبة عبر الإنترنت للضاغط ، باستخدام شبكات عصبية اصطناعية من النوع متعدد الطبقات (MLP). الهدف من عملنا هو اقتراح تصحيحات على نظام Di-Tronics2 حتى يتمكن من تحديد نوع العطل الذي يمكن أن يحدث على هذا الضاغط بدقة.

كلمات مفتاحية : ضاغط ، صيانة ، ضاغط طرد مركزي.

## Résumé

Dans ce projet, nous avons constaté que la maintenance préventive joue un rôle clé pour assurer le bon fonctionnement et l'excellente efficacité du compresseur centrifuge. Objet de notre étude. Comme on le sait, ce type de maintenance sert à prévoir le type de problèmes avant qu'ils ne surviennent, ce qui offre un moyen très utile d'augmenter la durée de vie de nos compresseurs.

Notre objectif est de proposer et d'implémenter dans Matlab une approche pour le développement d'un système de surveillance en ligne du compresseur, utilisant des réseaux de neurones artificiels de type perceptron multicouche (MLP). Le but de notre travail est de proposer des rectifications sur le système Di-Tronics2 afin qu'il soit en mesure de préciser avec précision le type de panne pouvant survenir sur ce compresseur

Mots clé : compresseur, entretien, compresseur centrifuge.