CHAPTER SEVEN

Guidelines for the implementation of a predictive maintenance program

Introduction

Conditioning monitoring systems evolved from predictive maintenance programs. The description of these programs will illustrate the definition of CMS and will provide the basis for their interpretation. This chapter remarks on the effects of a predictive maintenance program on productivity and product quality. It describes the steps to be taken to implement a predictive maintenance program. Maintenance has evolved through time; at the beginning, equipment malfunctions were repaired only at the moment they showed up (corrective maintenance). Afterward, the industry developed preventive maintenance systems that consist of repair actions based on statistical studies of the frequency of faults as well as recommendations from the manufacturer. These maintenance systems became expensive because only some of the repairs were needed. Then predictive maintenance systems were developed. They are based on periodic monitoring of the operating conditions of the machines and the application of techniques to estimate the expected life remaining in each component. These systems allow the scheduling of repairs and prevent unexpected failures.

Currently, it is convenient that all production systems based on continuous improvement techniques include, as a fundamental part of their scheme, predictive maintenance because it allows the total operation of the plant to be adjusted dynamically based on the actual operating conditions.

Predictive maintenance is a system that not only benefits the maintenance area, but also influences the improvement of productivity, the quality of the products, and the profitability of the investment. Therefore, it should not be taken only as a monitoring system but also as an integral part of the production strategy in a plant.

Mechanical Vibrations and Condition Monitoring
https://doi.org/10.1016/B978-0-12-819796-7.00007-X

Predictive maintenance consists of periodically monitoring (sample) the operating conditions of the machinery as well as analyzing the behavioral tendencies of each component. With this information, it is possible to estimate the time in which failures will occur. In this way, maximization of the repair intervals is achieved as well as minimizing the operating costs associated with premature or catastrophic failures and emergency stoppages of the machinery. To emphasize the concept, in this chapter a machine train is defined as three or more machine components that are coupled together, acting as one machine. The predictive maintenance systems are based on the different nondestructive techniques of analysis, among which the following stand out:

- *Vibration monitoring*: This technique consists of measuring the amplitude and vibration frequency of the critical components that form the machine train. This method was discussed extensively in the previous chapters.
- *Monitoring of the parameters of the process*: This is the main element of the predictive maintenance system. It consists of periodically recording the real values of all the parameters of the machine train (consumed power in electric motors, air pressure in pneumatic systems, hydraulic pressure, steam pressure, temperature, etc.). The purpose of this method is to relate variations in the measured variables with the probability of failure. The selection of the variables depends on the structure of the machine train and the type of individual components.
- *Thermography*: This method is based on measuring the temperature at different points of the machine train. This measuring provides related information to the mechanical behavior of each component because when a fail starts in any element of the machine train, usually the temperature increases. In this way, the changes in temperature can be associated with a machinery component with the possibility that it fails.
- *Oil analysis*: This technique is used as a complementary tool that analyzes the origin of the substances that contaminate the lubricants. The analysis helps to infer which of the components of the machine train is suffering premature wear or a more accelerated deterioration.

Among these techniques, vibration monitoring is the one that covers the most significant number of failure causes. Each of them occurs at a particular vibration frequency (as was seen in previous chapters) and their amplitude is a reflection of the machinery dynamic conditions. Besides, this amplitude in general increases according to the failure. The estimation of the time-to-failure stage defines the maintenance program. This estimation permits planning the entire production, meaning that the supply of spare parts can be done "just in time" and the maintenance activities can be determined ahead of time.

Predictive maintenance does not substitute for traditional maintenance systems; it is merely a tool that produces updated information allowing the evaluation of the future behavior of the equipment. The tendencies of all critical equipment can be graphed and estimated with a perfect approximation of the moment in which failure will occur. With vibration analysis, it is ensured that the repair intervals of the machinery will be extended and that the machine train offers the maximum availability of use. The benefits of predictive maintenance systems can be summarized as:

- Lower maintenance costs
- Lower number of failures
- Lower repair times
- Inventory reduction
- Increase the machinery lifespan
- increase in plant productivity
- Improvement of operational safety
- Verifications of operating conditions of new equipment
- Verification of repairs
- The possibility to implement "just in time" programs

Predictive maintenance programs start with the selection of the equipment to be monitored, the selection of the monitoring route, and the definition of the measuring intervals. Both the narrow bands and the alarm levels to each measuring point within the monitoring route are defined so that the tendency graphs are finally built, allowing the predictive dynamic behavior of the equipment.

Definition of the monitoring route

For the implementation of the predictive maintenance program, all fundamental machines for the production process of the company must be selected. In this way, a database with the most relevant information and the operation efficiency is built.

In each machine, both the measuring points and the monitoring periods are identified. For each monitoring point, the total vibration spectrum is recorded (full firms), and the zooms around the characteristic frequencies are analyzed, in this way, it is possible to establish the starting point of the predictive maintenance program.

Subsequently, the monitoring intervals must be established to build the tendency curves and in this way schedule the repairs. When there are no initial reference points, it is therefore recommended to monitor each selected point at intervals of between 8 and 15 days. Once the data for the first five points are established, the most suitable inspection intervals can be determined with the objective of "measuring the vibrations at lower time intervals than the intervals in which variations are detected in the measured signal in normal operating conditions." This procedure minimizes the possibility of a catastrophic failure.

Fig. 7.1 presents the curve of failure frequencies of pieces of equipment from their installation until removal from production. This graph is known as the curve of life because it resembles human life. It defines three phases: youth, maturity, and old age.

- Youth
- Productive life
- Elder

In the youth phase, the failures are greater due to their initial adjustments, premature wear, settlements, or design changes. The mature stage is considered to be the productive lifespan of the equipment. In the old age stage, the failures increase due to the deterioration of all the systems.

The objective of predictive maintenance is to get the machine train to operate as long as possible in its production life stage at the lowest possible cost. In this way, it would be ideal that the machine be substituted out due to a significant change in technology and not because it has reached its old age.

For the correct identification of the measuring points, it is essential to know the design of the machine train as well as the functioning details of the components, such as the rotation speeds of each shaft that form the gear, the type of supports (ball bearings, bearings), the type of power equipment (turbine, electrical motor, internal combustion motor, etc.), and their operational parameters.

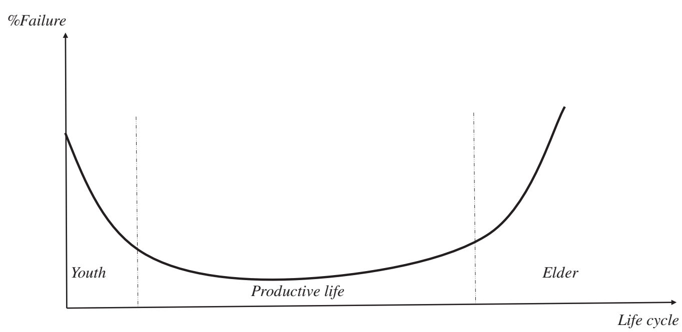

Fig. 7.1 Life curve of a machine train.

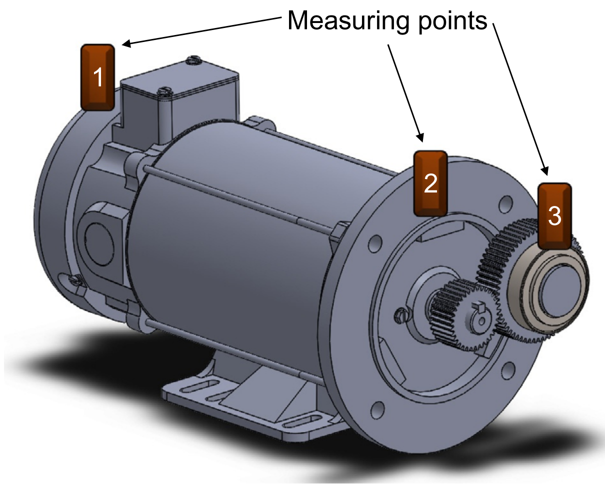

Fig. 7.2 Components of a machine train and the location of monitoring points.

Fig. 7.2 is a schematic representation of a typical machine train. The numbering of the points where the vibratory firms are measured every sampling time is indicated. It is recommended to carry out the numbering sequence from the end support of the motor and culminate with the end support of the output shaft. In this way, there is an ordered sequence of points and information can be handled with more detail. In each point, the direction of the signal must be identified. For example, in Fig. 7.2, point 1 would allow identifying the level of vibration of the train in three directions: horizontal, vertical, and radial. Once the route is established, at each monitoring point the narrow bands are defined.

Narrow band selection

Once the monitoring points in the gear train are located, the most outstanding characteristic frequencies of the vibration sources are identified. Around each of these frequencies, it is required to select the narrow bands to monitor before setting both the alert and alarm limits. These bands must contain the characteristic frequency as well as covering variations in the operating speed that are generally between 10% and 20% of the characteristic frequency when the speed variations of the equipment are small.

As a general guide, in Table 7.1 the frequencies are indicated where more information from the vibratory signal can be obtained, depending on the type of failure under study.

Table 7.1 Frequencies and the sideband limits for different failure modes.

Type of failure	Characteristic frequency (×)
Imbalance	Rotation frequency of each of the shafts with a bandwidth of 10% in the radial direction
Misalignment	Rotation frequency and its first harmonic with a bandwidth of 10% in both the radial and axial directions
Bent shaft	Rotation frequency and its first harmonic with a bandwidth of 10% in both the radial and axial directions
Eccentric shaft	Rotation frequency and its first harmonic with a bandwidth of 10% in both the radial and axial directions
Mechanical clearance	Rotation frequency of each shaft and to 0.5 ×, 1.5 ×, and first harmonic (2 ×) in the radial direction
Journal bearings	Rotation frequency and its first harmonic with a bandwidth of 10% in the radial directions
	In addition to a narrow band between 0.42 × and 0.5 × in the radial direction
Belts	Rotation frequency of each of the shafts with a bandwidth of 10% in the radial direction
	Pass frequency of the band and its first harmonic with a bandwidth of 10% in the radial direction
Electrical defects	Rotation frequency with a bandwidth of 10% in the radial direction
	Pole pass frequency
	Rotor bar pass frequency including at least four sidebands per side
	Line frequency including at least four sidebands of the sliding frequency and its first harmonic
Hydraulic and aerodynamic	Rotation frequency with a bandwidth of 10% in the radial direction
	Blade pass frequency and at least four sidebands
	Turbulence (from 50 to 2000 cycles per minute, randomly)
	Cavitation (In the case of the pumps, a signal appears between 0 and 1 ×, randomly.)
Roller bearings	Inner race pass frequency with a bandwidth of 20%
	Outer race pass frequency with a bandwidth of 20%
	Ball pass frequency with a bandwidth of 20%
	Rolling-element pass frequency with a bandwidth of 20%
Gears	Rotation frequency of each of the shafts with a bandwidth of 10% in the radial direction
	Gear frequency including at least four sidebands and the first harmonic of the gear frequency

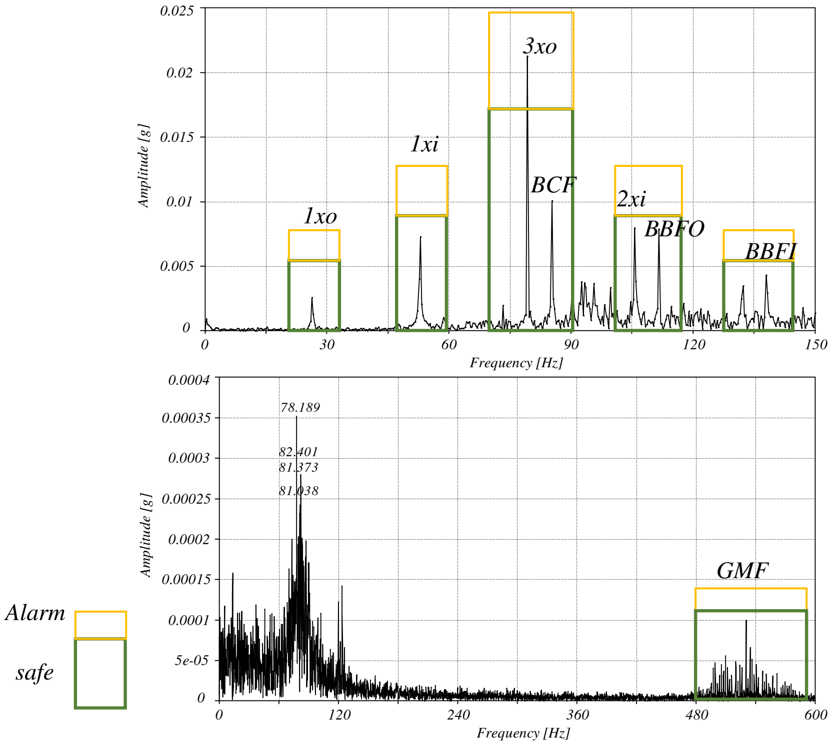

Fig. 7.3 Example of a frequency spectrum with the location of the narrow bands.

Once the narrow bands are determined, the predictive maintenance program starts, analyzing the tendencies of the dynamic behavior of the selected gear train. In Fig. 7.3, a spectrum with its narrow bands is shown.

Analysis of tendencies

Once the narrow bands in each monitoring point of the gear train under study are established, the permissible limits of the vibration levels are defined. The selection of these limits depends on the behavior of each machine, its importance in the production system, and the experience of the maintenance staff. As a general rule, it is recommended to establish the alert limit of measurements to twice the average value of the vibration amplitude in normal operating conditions, and the alarm limit to five times this latter value.

In general, the behavior of the vibration follows an exponential law. Therefore, when the vibration level reaches the alert level, the tendency curve can be traced and a date in which the vibration would reach the alarm limit can be objectively determined. During this period, repair or removing the machine from production must be done (Fig. 7.4).

The periodic monitoring of the vibration allows the stage of the life curve in which the gear train is located to be identified. The problem of tendency analysis is that it does not allow establishing the causes that produce the deterioration of the equipment. For that reason, it is necessary to complement the analysis with other information such as the reports of the operating conditions, the thermal analysis, the oil analysis and knowledge of the equipment design. This type of analysis complements the understanding of the equipment behavior, making the predictive maintenance more efficient.

Because the vibration in a machine does not keep the same levels of amplitude through its lifespan, it is necessary to provide a statistical followup to the behavior of the frequency under study to properly establish both the alert and alarm limits. Among the causes that produce the variation of the vibration amplitude, the changes in the operation of the machinery, climate changes, and the deterioration of the equipment itself stand out.

The analysis of the tendencies of the dynamic behavior of the machinery is the basis of the predictive maintenance system. To best illustrate its application, it is necessary to consider the subsequent example.

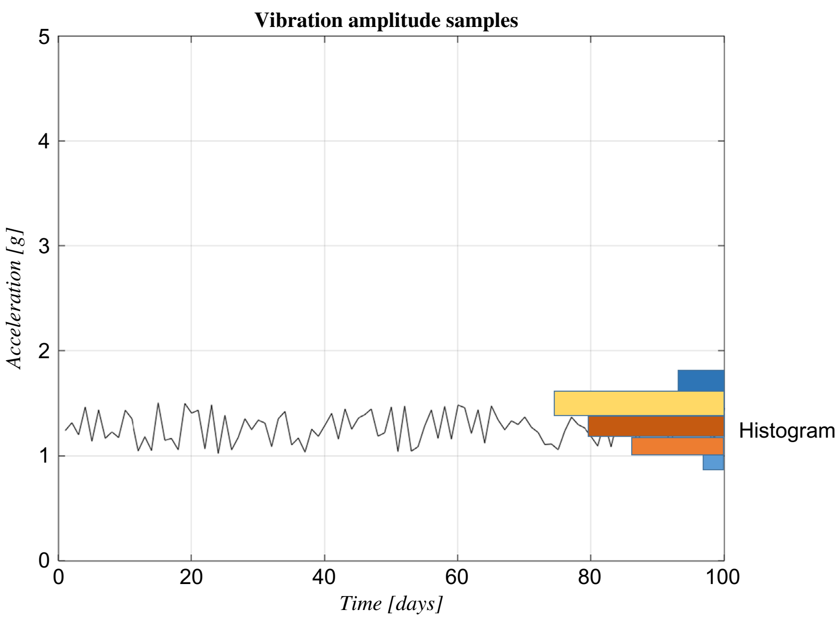

Fig. 7.4 Analysis of tendencies and histogram.

Example

In a chemical plant, there are two turbo-generators identical to the one shown in Fig. 7.5. The current importance of such equipment requires including them in the productive process. They were included in the predictive maintenance program of the entire installation. The turbo-generator can be defined as a machine train consisting of:

- A two-stage steam turbine with 135 and 150 blades, respectively, with a centrifugal governor for speed control.
- A gear reducer of a single-stage double-helical type with 21 teeth in the pinion and 97 in the gear, lubricated with a gear pump of eight teeth connected to the pinion shaft mounted on hydrodynamic ball bearings; the gear is mounted on bearings of 12 balls with diameters of ball pass $D = 235$ mm and $d = 40$ mm for each ball.
- Electric generator of six poles with a synchronous speed of 1200 rpm. The rotor is mounted on journal bearings.

Once the design is identified, the characteristics of all the components and the monitoring route are defined.

In this example, the dominant frequencies that each element generates are determined next.

Monitoring route

For the example, four monitoring points were selected. The first was at the free end of the turbine and the latter at the free end of the generator.

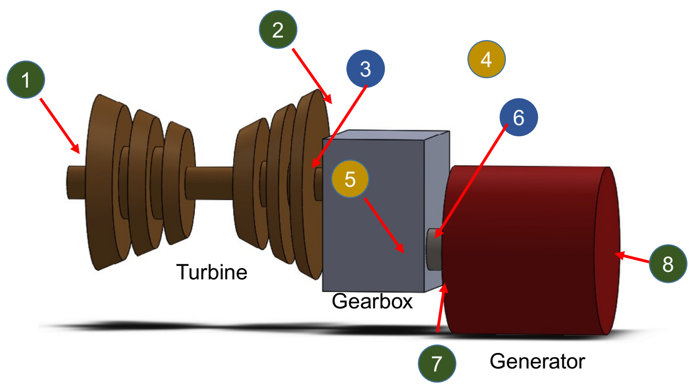

Fig. 7.5 Schematic representation of a turbo-generator.

In each measuring point, the frequency ranges were determined in which spectra were recorded as well as the frequencies of interest. For this, the frequency values that characterize each component of the turbo–generator were calculated. In this case, the rotation frequency of the turbine shaft (point 1) was calculated, depending on the gear reduction relation, in such a way that:

$$\begin{aligned}\omega_T &= \left(\frac{n_c}{n_p}\right)\omega_G\\ &= \frac{97}{21}(1200) = 5542.8\ cpm\end{aligned}$$

The blade pass frequency was calculated as:

$$\begin{aligned}FP_{A1} &= N_{A1}\omega_T\\ &= (135)5542.8\\ &= 748,285.7\ cpm\end{aligned}$$

And for the second pass:

$$\begin{aligned}FP_{A2} &= N_{A2}\omega_T\\ &= (150)5542.8\\ &= 831,428.5\ cpm\end{aligned}$$

For point 2, the rotation frequency of the pinion is the same as that of the turbine, so in these points, the frequencies of interest were those of the gear, the one of the teeth pass of the lubrication pump, and those associated with the problems of the hydrodynamic ball bearing.

The gear frequency is:

$$\begin{aligned}FE &= n_p\omega_T\\ &= (21)5542.8\\ &= 116,398.8\ cpm\end{aligned}$$

For the lubrication pump:

$$\begin{aligned}FE_B &= n_B\omega_T\\ &= (8)5542.8\\ &= 44,342.4\ cpm\end{aligned}$$

And for the ball bearings, a range between 0.35 and 0.5 was estimated, and Fch was:

$$Fch = 1940 \text{ to } 2770\ cpm$$

In point 4, the vibration was measured at the rotation frequency of the gear (8w = 1200 rpm) and to the frequencies that characterize the bearings:

$$FRB = \left({}^{1}/_{2}\right)\left(1 - r^{2}\right)x$$
$$FRP = \left({}^{1}/_{2}\right)(1 - r)x$$
$$OBPE = \left({}^{n}/_{2}\right)(1 - r)x$$
$$OBPI = \left({}^{n}/_{2}\right)(1 + r)x$$

With the data of the ball bearings, the fundamental frequency of the bearing (fundamental train frequency) was determined, having:

$$FRP = 497.87\ cpm$$

The ball spin frequency is:

$$FRB = 3422.8\ cpm$$

The frequency due to a fault in the outer race is:

$$OBPE = 59744.4\ cpm$$

And the frequency due to a failure in the inner race is:

$$OBPI = 8425.53\ cpm$$

In the measuring points that correspond to the electrical generator, both the power line frequency and its harmonics (in this case, there is no slip frequency) were specified, in addition to the rotation frequency.

$$F_L = 3600\ cpm$$
$$2F_L = 7200\ cpm$$

Once the characteristic frequencies and the narrow bands for each of the selected measuring points was identified, the narrow bands were selected based on the previous information in this chapter, rounding their values according to the resolution of the used vibration analyzer equipment (Table 7.2).

Analysis of tendencies

Once both the monitoring route and narrow bands were established, it will proceed to the capture of the frequency spectra. At the beginning of the program, it is required to monitor the system under study with higher frequency. This frequency depends on the type and operating condition of the gear train. However, as an average value, it is estimated that by carrying out

Table 7.2 Characteristic frequencies and narrow bands of the measuring points selected.

Measuring point	Direction	Reference frequency (cpm)	Side bands
R01	Radial	5500	5000–5750
		11,100	10,000–12,200
Z01	Zoom (radial)	750,000	725,000–770,000
R02	Radial	5500	5000–5750
		11,100	10,000–12,200
Z02	Zoom (axial)	830,000	810,000–855,000
R03	Radial	2300	1940–2780
		5550	5000–5750
		11,000	10,000–12,000
A03	Axial	5500	5000–5750
		11,100	10,000–12,200
Z03	Zoom	116,000	93,800–138,000
R04	Radial	2300	1940–2780
		5500	5000–5750
		11,000	10,000–12,000
A04	Axial	5500	5000–5750
		11,100	10,000–12,200
R05	Radial	500	400–600
		1200	1100–1320
		2400	2200–2600
		3400	3000–3500
		6000	5750–6600
A05	Axial	1200	1100–1320
		2400	2200–2600
R06	Radial	500	400–600
		1200	1100–1320
		2400	2200–2600
		3400	3000–3500
		6000	5750–6600
A06	Axial	1200	1100–1320
		2400	2200–2600
R07	Radial	1200	1100–1320
		2400	2200–2600
		3600	3550–3650
		7200	7150–7250
A07	Axial	1200	1100–1320
		2400	2200–2600
R08	Radial	1200	1100–1320
		2400	2200–2600
		3600	3550–3650
		7200	7150–7250

measurements every 15 days, a pattern of behavior of the mechanical rotating equipment can be established. With the information collected, the analyst graphs the tendency curves for each point and adjusts the reading intervals according to the equipment performance.

Even though a large amount of data is handled, modern computer systems allow its analysis in real time, which facilitates its handling, allowing the maintenance engineer to define both the inspection intervals and the repair of the machinery with objective criteria.