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Research Article

Towards a New Methodology for Setting Vibration Thresholds

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Abstract

The setting of alarm thresholds and breakdowns is a key point in the implementation of monitoring and vibration diagnosis. So, after the choice of monitoring indicators, it is required to determine the thresholds to use in monitoring rotating machinery. In fact, any significant overrun of the measured value to the reference thresholds must lead immediately to trigger a diagnostic procedure. In most cases, the maintenance technician refers to the international standards to set these thresholds. However, the use of these standards can lead to error, because the proposed criteria do not take into account the nature of the defects. Therefore, it is difficult from the thresholds of these norms to trigger an intervention on the machine, modify the measurement period or to bring detailed monitoring. This paper aims on the one hand to present the different norms in vibration and their main gaps and on the other to propose a process for monitoring and fixing the vibration monitoring thresholds.

Keywords: *Vibration Analyses, Industrial Maintenance, Rotating Machinery, Vibration Thresholds, Norms, Vibration Diagnosis.*

1. Introduction

Vibration analysis with a view to Vibration based analyses is a powerful tool for industries during the last few decades (Estocq, 2004). Its use is to serve two levels of analysis: monitoring and diagnostic of equipment status (Augeix, 2000). The purpose of surveillance is to monitor a machine by comparing successive records of its vibrations. Therefore, an upward trend of some indicators compared to reference values constitute the signature that typically alerts the technician on one probable dysfunction (Boulenger, 2008).

Generally, the diagnostic system used in industrial plants is to obtain an overall amplitude of vibration (Boulenger, *et al*, 2009), and make a trend analysis. When an alarm value is reached, the spectral analysis should be performed (Bosmans, 1982). After exceeding the breakdown alarm, the following sequence is recommended: (i) obtain the spectrum; (ii) monitor the status of abnormal harmonics; (iii) undertake a maintenance task to remove these harmonics (Borda, 1990).

Most manufacturers and decision makers refer to vibration standards to fix the vibration alarm thresholds (Boulenger, *et al*, 2007). But despite that there is a variety of standards developed and published by international organizations (Robichaud, 2004), there is a difficulty in determining the reference thresholds to ensure a good vibration monitoring. Thus, the use of assessment standards showed that there are still gaps that prevent industries to achieve desired objectives of this form of maintenance.

The only one standard is insufficient to make a reliable monitoring of vibration analysis. Since there is no direct link with the defects sought and reference thresholds, we must look for other methods that take into account the operating conditions (load, speed, temperature, variability ...) (Boulenger, 2008) , (Yang, *et al*, 2013). The constancy of the conditions of use of a collect to another is rarely verified in practice and even a significant overshoot of the measured value does not necessarily result in occurrence of a fault. In this paper we are going to review the different standards that have emerged in recent decades by showing their weaknesses in practice or in the field. In addition, we will propose a process to define the different vibration monitoring thresholds.

2. Vibration standards

Over the past seventy years, dramatic improvements have occurred in technology and practice used for measuring, monitoring and vibration analysis of rotating machines (Fig. 1). Among which we mention the emergence of standards for evaluation of vibration measurements (Mitchell, 2007).

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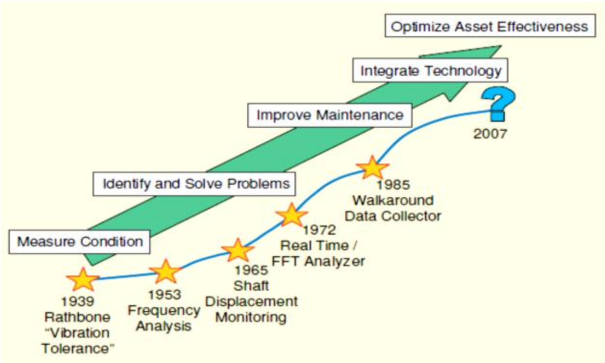


Fig.1 Evolution of measurement and monitoring techniques of vibration analyses (Mitchell, 2007)

Standards are documented agreements containing technical specifications or other precise criteria to be used consistently as rules, guidelines or definitions of characteristics, and to ensure that materials, products, processes and services are fit for their purpose (Robichaud, 2004). In the field of vibration analysis, the International Organization for Standardization (ISO) published in 1974 two vibration standards (Mitchell, 2007):

- ISO 2372: Mechanical vibration of machines with an operating speed between 10 and 200 rpm- Basis for developing evaluation standards (based on the German VDI 2056);
- ISO 3945: Mechanical vibration of large rotating machines in the range of speeds between 10 and 200 rpm - Measurement and evaluation of vibration severity in situ.

Today there are a variety of standards that are widely accepted and applied in the field of maintenance and scientific research (Thomas, 2012):

- ISO 2372, 3945, 7919 et 10816
- VDI 2056, DIN 45665 (Germany)
- BS 4675 (England)
- API standard 610, 612, 613, 617, 619,… (USA)
- CDA-MS-NVSH 107 (Canada)

These norms intend, firstly, to facilitate vibration monitoring in terms of setting thresholds, establishment and classification of rotating machines and choice of methods of measurements taking and processing. They were standardized with slightly different criteria depending on the country and according to the power, the type of machine or application.

For the exploitation of these standards, the measurement must be done when the rotor and the bearings have reached their normal operating temperature stability and when the machine is running in nominal conditions (pressure, flow, pressure, load, speed, ...) (Thomas, 2012). Unfortunately, each machine is installed in a different way and has to work in unpredictable conditions. It is unrealistic to want to achieve absolute vibration severity (Boulenger, *et al*, 2009).

3. Problem of determining vibration threshold

In industry, even identical machinery rarely have the same operating conditions and installation. In addition, the surrounding areas also differ (temperature, insulation, humidity, air pollution ...). So under these conditions, maintenance decision makers often find it difficult to define a selection of criteria to implement condition-based maintenance (Iso, 1999).

Let's the example of two cruchers installed in the same installation. They both have the same kinematic diagram (Fig. 2) and the same characteristics (Fig. 3).

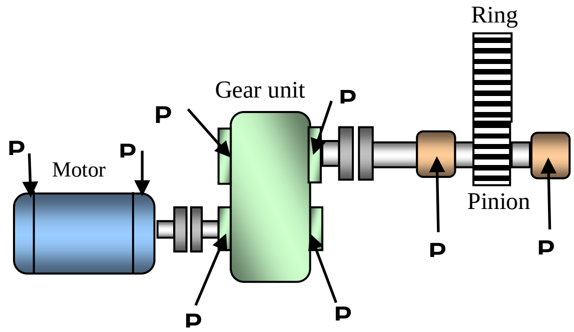


Fig.2 A kinematic diagram of the two cruchers studied

Motor		**pinion gear**	
Nominal speed:	992 t/min	Pitch diameter :	636 mm
Power :	1750 KW	Number of teeth :	21
power supply :	6000 V		
Gear unit		**Ring**	
Power :	2100 HP	Pitch diameter :	6664 mm
Input speed :	985 rpm	Speed :	15 rpm
Output speed :	150 rpm	Absorbed power :	1550 KW
		Number of teeth :	220

Fig.3 Characteristic of the two studied cruchers

Among the vibration measurements made on the points P1 to P6, Figures 4, 5 and 6 represent the running tranquility of these two crushers measured on the points P3, P4 and P5 in the horizontal direction. These measurements were recorded in 2014.

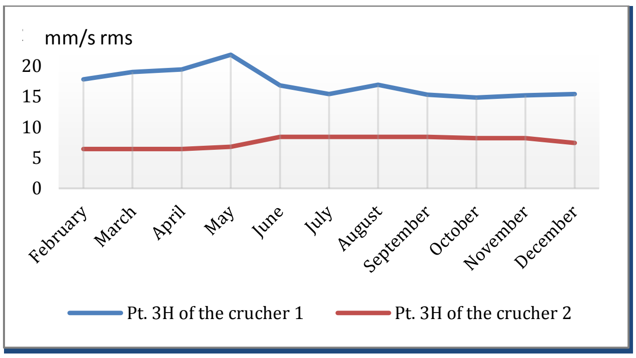


Fig.4 Tranquility running of the two crushers 1 & 2 measured at the point P3

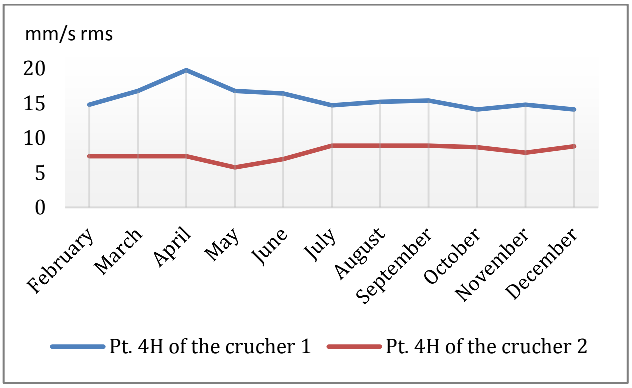


Fig.5 Tranquility running of the two crushers 1 & 2 measured at the point P4

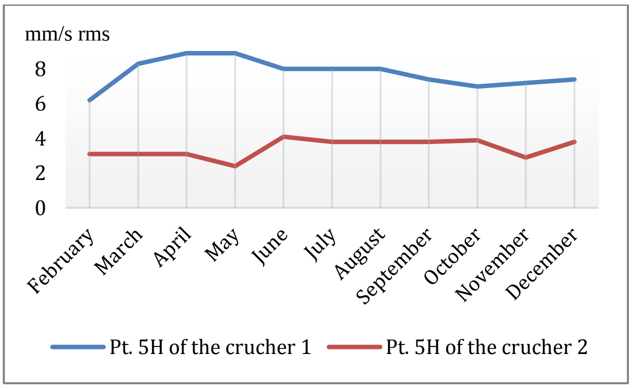


Fig.6 Tranquility running of the two crushers 1 & 2 measured at the point P5

These three graphs show that there is a huge gap between the recorded vibrations, at the same points for the two crushers which are expected to be identical. In addition, the crusher No.1 vibration values exceed the critical alarm thresholds recommended by the 10816 standard (see Group III of the standard shown in fig. 7), and the crusher continues to operate normally without any malfunction. Thus, it is difficult in this situation for a maintainer to determine vibration thresholds enabling good vibration monitoring.

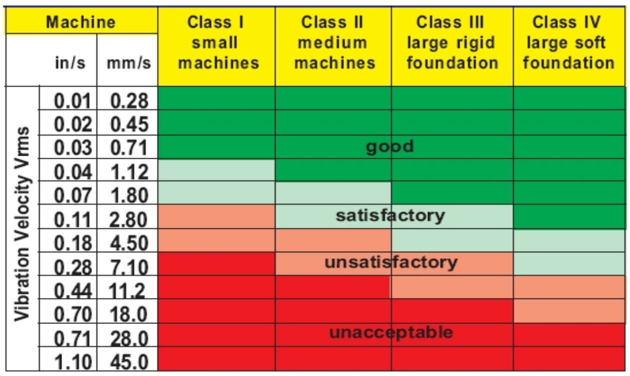


Fig.7 Thresholds recommended by ISO 10816

This example clearly shows the limits of the rates in determining vibration thresholds. Our job then is to propose an effective approach for the evaluation of vibration thresholds in all conditions of operation of the machine to be monitored and the surrounding environment.

4. Deficiencies of standards in determining the threshold of vibrations

To ensure vibration monitoring, we proceed to the measurement of overall level of vibration either on displacement, on speed or acceleration (Thomas, 2012), (Boulenger, *et al*, 2007). Today, the standards provide reference values of displacement and speed (Mitchell, 2007), (Augeix, 2000). As for the acceleration which is a general indicator, it is used by experts to monitor bearings and gear units.

For a given scalar indicator, it must first choose a suitable sensor and a frequency band before addressing measure (Boulenger, *et al*, 2009). Noting that each standard of vibration allows the assessment of the state of the machine in a frequency band specified in the standard (see Table. 1) (Augeix, 2000).

Table 1 Frequency band for vibration measurement indicator (Augeix, 2000)

Indicator	*vibration measurement indicator*	*Monitored Phenomenon*	*Observation*
Peak to peak displacement	[10 – 1000 Hz]	Low Frequencies	API standards (petrochemistry)
Speed (rms)	[10 – 1000 Hz]	Low and high frequencies	ISO 10 816 standard
Acceleration (rms)	[1000–30000 Hz]	High frequencies	General indicator

However, the use of standards for defining reference values, including the standard 10 816 which is the most commonly used (Iso, 1999), was not satisfactory in the industries (Boulenger, *et al*, 2009), (Kostyukov, *et al*, 2015). For it must be noted that there is a wide range of defects (imbalance, misalignment, friction, bearings instability, loosening, spills of ring bearings, bearings chipping, chipping of gear teeth ...), but the criteria given by this standard are unfortunately used only to monitor the defects of imbalance. (Boulenger, *et al*, 2009) Whereas for the severity of other defects of vibration, the proposed criteria are more often far too high. So under the standard, the fact of being in a permissible measurement range does not necessarily mean that the latter does not already present an accelerated or normal deterioration signs.

Referring to the norms of vibration to set thresholds has many shortcomings:

- The given thresholds have no direct relation with the cause that generates the fault. This causes an ambiguity for those in charge of vibration monitoring.

- The thresholds do not take into account the masking effect which remains a major problem limiting considerably the reliability of using norms. In fact the measurement being "global", the measured vibrational energy is the sum of all the vibrational energies induced by dynamic forces "normal" and "abnormal" in which the machine is the seat. If A_{GN} represents the effective amplitude of the vibrational contribution of dynamic forces induced by the normal operation of the machine and the A_{GD} effective amplitude of that induced by the set of failures or malfunctions, the overall effective measured amplitude is equal to $\sqrt{A_{GN}^2 + A_{GD}^2} = A_{GN}\sqrt{1 + \left(\frac{A_{GD}}{A_{GN}}\right)^2}$. This relation shows that for the overall measured level to be sensitive to the occurrence of a defect, the vibrational energy induced by the latter has to be significant compared with that induced by the normal operation of the machine, which is, unfortunately, not always the case. Taking the example of a blower motor (Fig. 8), the value of the indicator of the overall level in Veff measured on a bearing is 3.24 mm/s. In reality this value is calculated as follows:
  $V_{RMS} = \sqrt{3^2 + 0{,}5^2 + 1^2 + 0{,}5^2} = 3{,}24$ mm/s, including:
  - 3 mm/s represents an imbalance;
  - 0.5 mm/s represents a misalignment;
  - 1.0 mm/s represents an effort gear;
  - 0.5 mm/s represents a chipping affecting the inner ring of the rolling bearing of the turbine.

So if the unbalance level increases by 30% there will be a global ($\sqrt{3{,}9^2 + 0{,}5^2 + 1^2 + 0{,}5^2}$ = 4,08) mm/s resulting in an increase of 26% of the former value. contrariwise the amplification of the defect of the inner ring of the bearing by 3 times results in an overall level ($\sqrt{3^2 + 0{,}5^2 + 1^2 + 1{,}5^2} = 3{,}53$ mm/s) which represents only a 9% increase from the first measurement. However, in the latter case, changing bearings should be programmed at the earliest (Boulenger, *et al*, 2009).

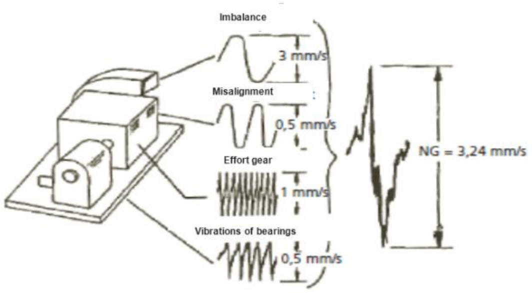


Fig.8 Different signals of the blower motor

- The classification of machines in these standards takes into account two criteria (power and foundation) (Thomas, 2012), while neglecting the specific evaluation criteria for each type of machinery (pump, fan, gear, compressor, alternator, turbine…).
- The assessment criteria proposed by the standards insufficiently reflect the different speeds at the level of equipment. If we take the example of the turbo blower of fig. 9, it is noted that there are two widely different speed shafts (Fig. 10). Now, since the vibration has a relationship with the rotation speed, there will be practically a significant gap between the measures taken at the points P1 and P2 of the blower shaft and P3, P4 and P5 of the turbine shaft.

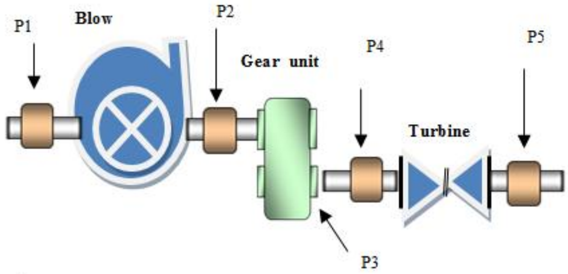


Fig.9 Kinematic diagram of the turbo blower

Turbine :	Nominal speed	11890 RPM
Gearunit :	Input speed	11890 RPM
	Output speed	2670 RPM
	Nb of input teeth	64
	Nb of output teeth	285
Wheel :	Nominal speed	2670 RPM
Bearing :	Oil bearing	

Fig.10 Characteristics of the turbo blower

Table 2 shows that there is a significant difference between the measured values of the two shafts rotating successively by 11890 RPM and 2670 RPM. For example, 23 Aug. 2014, we recorded on the horizontal direction of P1 and P2 of the blower the two values 0.5 mm/s and 1.3 mm/s that are very different values of 4.8 mm/s, 5.4 mm/s and 7.5 mm/s measured successively in the same direction P3, P4 and P5.

Table 2 Running tranquility (mm/s) of the turbo blower recorded between 23 August 2014 and 05 November 2014

	BLOWER						GEAR			TURBINE					
	P1			P2			P3			P4			P5		
Date	H	V	A	H	V	A	H	V	A	H	V	A	H	V	A
23 Aug. 2014	0.5	0.4	1.7	1.3	0.9	1.7	4.8	5.6	3.2	5.4	3.8	2.9	7.5	2.1	2.7
06 Sept. 2014	0.5	0.3	0.6	0.6	0.6	1.4	3.9	4.8	4.4	3.9	4.7	2.4	6.1	1.4	1.6
20 Sept. 2014	0.6	0.5	1.9	1.9	0.8	1.8	3.4	6.5	3.9	6.2	4.7	2.8	5.1	1.1	1.2
23 Sept. 2014	0.5	0.4	1.6	1.6	0.8	1.8	2.9	4.6	3.7	4.1	2.7	1.6	4.7	1.4	2.1
10 Oct. 2014	0.5	0.3	1.3	1.3	0.4	1.3	3.5	4.3	1.9	4.6	4.6	2.3	6.4	1.2	1.7
25 Oct. 2014	0.4	0.4	1.1	1.1	0.8	1.6	5.1	7.6	2.6	4.9	4.9	4.4	8.2	5.6	6.8
05 Nov. 2014	0.4	0.4	1.4	1.4	0.9	1.7	3.5	6.6	3.9	4.3	4.3	3.2	6.9	4.1	4.5

- These standards were originally designed to provide general guidelines for the design and operation under certain conditions of rotating machines (Robichaud, 2004). However, the variation of the actual vibration values of a bearing due to the change of temperature, load and speed does not necessarily mean the presence of degradation. For the crusher No.1, vibration values of trend analysis of both P4 and P5 point for the years 2011, 2012, 2013 and 2014 shows that most of the measures exceed the threshold recommended by the ISO 10816 standard that is 11.2 mm/s without any defects recorded (fig. 11, 12, 13 and 14).

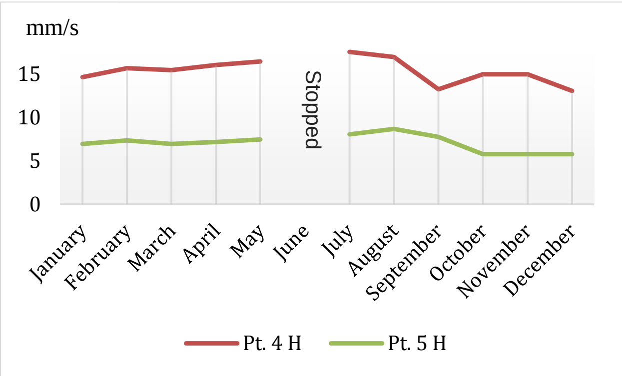


Fig.11 Tranquility of the turbo blower recorded in 2011

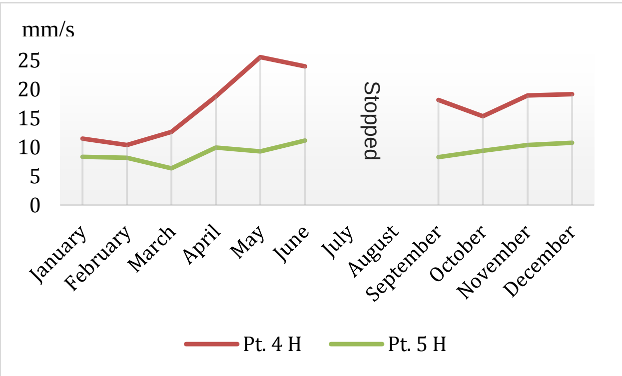


Fig.12 Tranquility of the turbo blower recorded in 2012

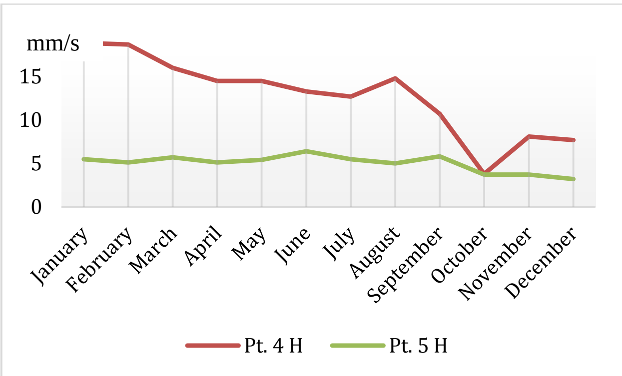


Fig.13 Tranquility of the turbo blower recorded in 2013

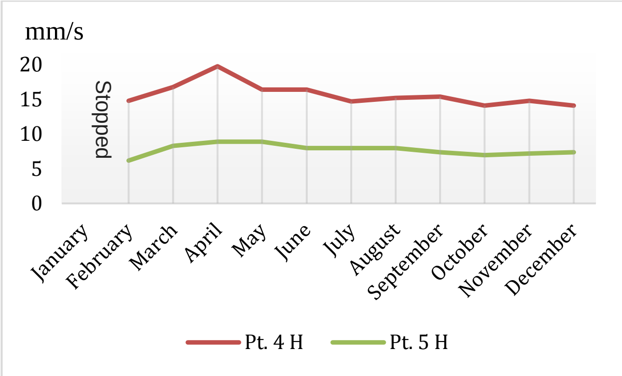


Fig.14 Tranquility of the turbo blower recorded in 2014

Therefore, the use of standards for setting vibration thresholds is not danger free. The evaluation criteria that do not take into account certain realities about the machine and its environment, the absence of links between the nature of vibration defects and the thresholds recommended by the standards and also the masking effect limits reliability of these standards for monitoring and diagnosis of vibration. This is why the thresholds recommended by the standards can induce to error and exceeding a threshold may not have to mean defect. Hence the need for a more reliable and efficient method for performing an accurate diagnosis of the facilities before being put under observation, define the thresholds and adjust them according to the actual condition of each machine. In this context, our work becomes part of offering an approach to objectively evaluate the vibration thresholds.

5. Approach for determining vibration thresholds

Given the difficulties of using these standards of vibration, a set of approaches have been developed for setting the reference thresholds based on the experience of the manufacturer or operator sometimes also statistics or old records of breakdowns such as that proposed by (Thomas, 2012) who uses expectancy and standard deviation measurements to define related alarm levels. Unfortunately , these references generally get applied on new machines, while, frequently, vibration monitoring is implemented on a set of machines running for many years and for which we have not undertaken any measures in while putting into service (Boulenger, *et al*, 2009). The aim of our study is to provide a comprehensive approach that applies to all machines while taking into consideration environmental and installation conditions.

In contrast to the proposed approaches, our approach begins with developing a pointed machine diagnosis in order to distinguish, at the level of vibrational spectrum, between measured signals due to vibration defects and those related to environmental and installation conditions . The values of these will be added to predefined thresholds by the standards to provide benchmarks allowing efficient monitoring of the actual state of the machine.

5.1 Stages in the approach (Fig. 15)

This approach consists of setting the reference thresholds based on the different spectra taken at each point of the installation. Indeed, as the spectrum allows us to have information about the vibration source and the degree of severity of the problem, we will use it to identify all the peaks that are due to environmental and installation conditions and other peaks that are abnormal.

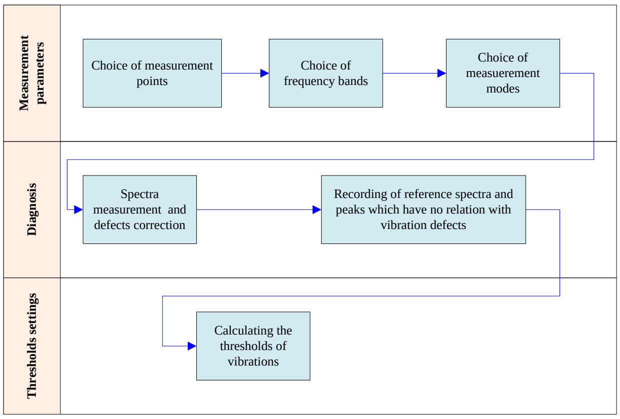


Fig.15 Proposed Approach for setting thresholds of vibration monitoring of rotating machines

To efficiently identify the reference values, taking into account all environmental and installation conditions, we proceed as follows:

1) We begin by the selection of measurement points. Thus, to take into consideration, the power and the rotational speed, we must arrange thresholds by rotation shaft.
2) We select a wide frequency band. So in order to integrate all the possible frequencies, we choose the next band [10-30000 Hz] that allows to visualize all the phenomena of low frequency and high frequency. If part of the frequency range contains no harmonics, the width of this band can be reduced.
3) For the measurement mode we choose the rotational speed which accentuates the low frequency peaks as well as the high frequency.
4) We measure the spectrum of the vibration and make a first diagnosis. At the level of this diagnosis we begin by identifying the source and severity of each peak. So depending on vibration analysis, we must take corrective action if the identified peaks provide information about a vibration problem (misalignment, loosening, belt defect, imbalance, bearing defect, ...).
5) After removing any abnormal peaks, we measure the reference spectrum and record the peak amplitudes which have no relation to defects of vibration.
6) Finally, the various thresholds are calculated by RMS using the following formula:

$$S = \sqrt{S^2 + A_1{}^2 + A_2{}^2 + \cdots + A_m{}^2}$$

With:

- S: threshold given by the ISO 10816 standard;
- A: Amplitude of the peak recorded in step 5 and which has no connection with the defects of vibrations;
- m: the number of peaks recorded in step 5 and which have no relation to defects of vibration.

5.2 Case Study of two crushers

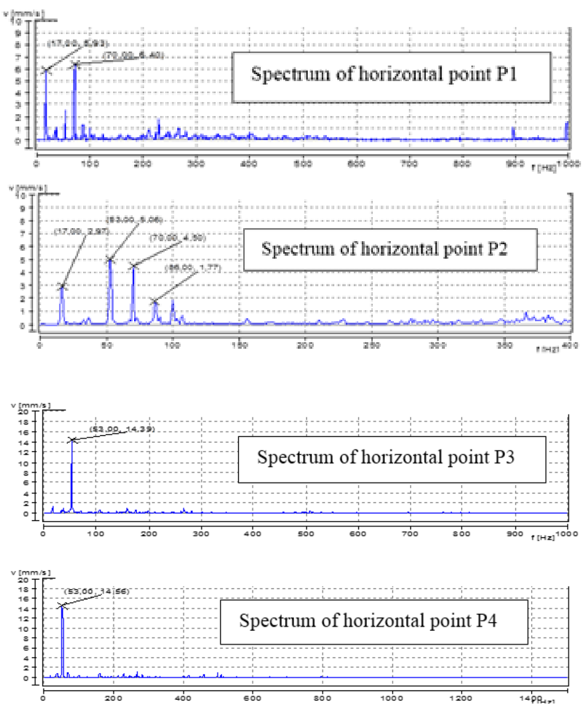
In this study we chose the two crushers 1 and 2 in Fig.2, to set different thresholds for vibration analysis through the application of our approach.

➢ Study of the crusher No.1:

We have set 6 measurement points as shown in Fig. 2:

- 3 points on the first speed shaft of 985 RPM
- 3 points on the second speed shaft of 150 RPM

The vibration measurement will be made, firstly in the frequency band [10-30000 Hz]. Afterwards, we will use the analyzer and data collector VibXpert II to record spectra of frequency ranges containing peaks (Fig. 16).



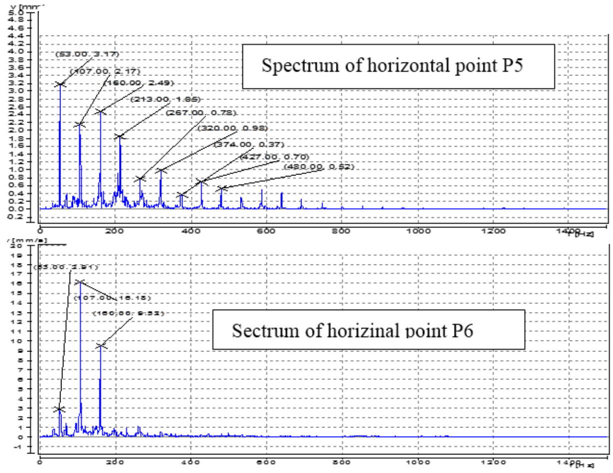


Fig.16 The spectra measured on points of crusher No.1

From the frequency analysis of the points P1 and P2, the highest peak is 6.40 mm/s at a frequency of 70Hz. This frequency corresponds to 2x 35 Hz which is that of pinion gear. Therefore it can be deduced that it is a problem of alignment of the latter. To eliminate this peak, mechanical service should carry out an alignment of the pinion gear.

At the level of spectra of the points P3 and P4, it is found that there is a peak of 14.5 mm/s at a frequency 53 Hz. This frequency corresponds to the meshing frequency. This is a frequency related to the operation of the crusher. It has no relation with a defect of vibration. Thus it is necessary to consider the amplitude of this peak in the setting of thresholds.

The two spectra of points P5 and P6 have harmonics of frequency 53 Hz. This reveals a backlash defect. The mechanical service should carry out the verification of the backlash at the level of the gear unit.

After the correction of the alignment of the pinion shaft and backlash in the gear unit we fix thresholds as follow (Table 3):

- For points 1 and 2, we keep the same thresholds given in the ISO 10816 standard;
- For 3 and 4 are added 14.5 mm/s to the thresholds given by ISO 10816. So the only critic 11.2 mm/s given by the current standard is 18.3 mm / s which is equal to $\sqrt{11.2^2 + 14{,}5^2}$ according to the formula of step 6.
- For points 5 and 6, we keep the same thresholds given in the ISO 10816 standard.

Table 3 New vibration monitoring thresholds for crusher No.1

Status\Point	Points 1 et 2	Points 3 et 4	Points 5 et 6
Good	Inferior to 1.8 mm/s	Inferior to 14.6 mm/s	Inferior to 1.8 mm/s
acceptable	between 1.8 and 4.7 mm/s	between 14.6 and 15.2 mm/s	between 1.8 and 4.7 mm/s
Still acceptable	between 4.7 and 11.2 mm/s	between 15.2 and 18.3 mm/s	between 4.7 and 11 mm/s
inacceptable	Superior to 11.2 mm/s	Superior to 18.3 mm/s	Superior to 11 mm/s

After analyzing the vibration measurements in points 3 and 4, the proposed approach shows that the crusher can operate up to a value of vibration of 18.3 mm / s (see Table 3). However, the fixed standard as critical alarm is 11.2 mm/s.

➢ Study of the Crusher 2:

- For the measurement points, we chose six measurement points as shown in Fig. 2
- For the measurement range, we chose the frequency band [10-30000 Hz].
- For taking measurements, we used the collector and analyzer Vibxpert II for the measurement of the following spectra Fig. 17:

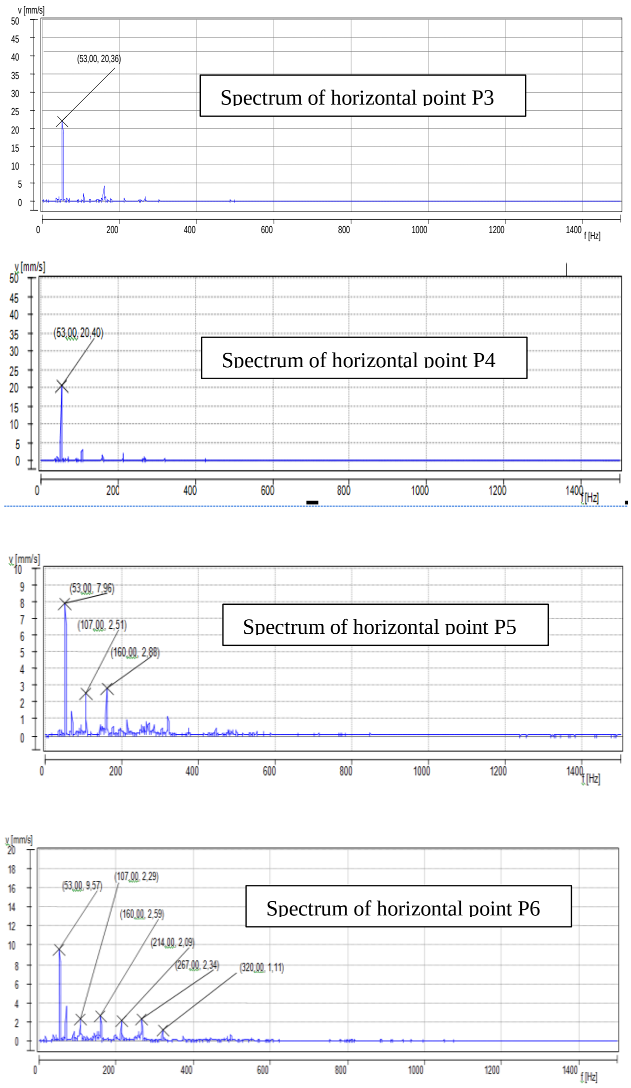


Fig.17 The spectra measured on points of crusher No.2

In this crusher, we recorded:

- A backlash meshing defect that requires intervention of the mechanical department (see spectrum of points 5 and 6 in Fig. 17)
- A peak of 20.4 mm/s at the meshing frequency 53 Hz which is related to the operation of the crusher

and shows no sign of any defects (see spectrum of points 3 and 4 in Fig. 17). The value of this peak should be integrated into vibration monitoring alarm thresholds.

After the correction of the backlash at the gear unit we set the thresholds as follow (Table 4):

- For points 1, 2, 5 and 6 we keep the same thresholds given in the ISO 10816 standard;
- For points 3 and 4 we added 20.4 mm/s to the thresholds given in the ISO 10816 standard.

Table 4 New vibration monitoring thresholds for crusher No.2

Status\Point	Points 1 et 2	Points 3 et 4	Points 5 et 6
Good	Inferior to 1.8 mm/s	Inferior to 20.5 mm/s	Inferior to 1.8 mm/s
acceptable	between 1.8 and 4.7 mm/s	between 20.5 and 20.9 mm/s	between 1.8 and 4.7 mm/s
Still acceptable	between 4.7 and 11.2 mm/s	between 20.9 and 23.3 mm/s	between 4.7 and 11 mm/s
inacceptable	Superior to 11.2 mm/s	Superior to 23.3 mm/s	Superior to 11 mm/s

This crusher can operate without defects up to a vibration value of 23.3 mm / s (see Table 4). It is worth noting that despite they are identical, the two crushers do not have the same thresholds.

With this approach we were able to combine between the thresholds set by the ISO 10816 standard and our diagnosis in order to link reference values with the actual operation of the plant.

Conclusions

In this study, we have put emphasis on the different standards that have emerged since the last 40 years. Through the study of actual cases of rotating machines (turbo blowers, grinders, gear systems) we have emphasized their limitations in practice. Then, we proposed an approach that allows to define the different vibration monitoring thresholds by exploiting the spectra taken on each point of the installation.

A industrial case study has been processed to validate the approach and show that in certain cases exceeding the thresholds imposed by the standards is not always synonymous with defect.

Currently, this approach is applied by the vibration analysis departement of the plant where they processed different case studies.

In perspective, this approach must be translated into a computer program for an automatic determination of thresholds.

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