Innovations

Towords Effective and Sustainable Management of Rotating Machine Monitoring and Diagnosis in the Cement Plant

Linda Bouyaya[1] & Rachid Chaib[2]

[1,2]Faculty Science of Technology, Transportation Engineering Department, University of Constantine 1, Laboratory Engineering of Transport and Environment, Constantine, Algeria

Abstract: *With the growing complexity of the industrial system and the rapid evolution of technologies, mastering maintenance function and assessing industrial risks have becoming strategic imperatives for safeguarding assets and ensuring operational continuity. In highly competitive environments, continuous improvement-one the fundamental principles of quality management- is essential to sustaining technological systems and enhancing their performance. This study focuses on identifying priority actions for management and control in cement plantsto prevent operational disruptions. It applies a posteriori failure analysis to determine root causes of disturbances that many lead to accidents, enabling the implementation of preventive measures and the reduction or elimination of such events. The objective is to develop and applya structured methodology to improve monitoring, diagnosis and overall maintenance performance.*

Keywords: *vibration analysis, FMECA, maintenance, spectral analysis, rotary kiln, cement plant.*

1. Introduction

The cement industry plays a crucial role in global economic and urban development and isanstrategic sector for the Algerian economy, given the essential cement in all construction projects. Numerous economic and social infrastructure construction projects have been completed, while many others are underway, driving a consistently high demand for cement. To meet this growing demand, mastering of the cement manufacturing process is essential [1].

Among the most critical stage of cement production is the rotary kiln, a key piece of equipment whose role is to heat raw materials to high temperatures to produce clinker, which is then ground in to cement [2]. Due to the extreme thermal and mechanical stresses to which it is subjected, to significant the rotary kiln is prone to mechanical failures and operation disruptions, which can significantly impact production and quality. One of the main challenge lies in the determining the most appropriate maintenance actions when failure occur, especially for equipment that play such a vital role in the process. This make continuous monitoring and early defect detection essential [3, 4].

Vibration analysis is among the most widely used techniques in condition-based maintenance for monitoring the health of bearings and other rotating component. It provide information on the functional condition of elements such as bearings, gears, shaft misalignment. Monitoring the evolution of vibration signature over time enables early detection of degradation, allowing proactive interventions to avoid unplanned downtime and costly repairs. Signal processing tools thus play a crucial role in maintenance during both diagnosis and prognosis stages of rotating machinery health [5, 6], the objective of our work.

Unliketraditional maintenance methods, which often involve repairing machines only after failures, modern approach focus on continuous interventions based on the monitoring key parameters such as temperature, oil pressure and most importantly vibration[7, 8]. For rotating machines, vibrations measurement is considered the most reliable and early indicator of deterioration. Analysis of vibration signatures allows engineers to diagnose operating conditions, stress the severity of faults, and determine of the urgency of corrective action [9].Rotating machines are complex systems composed of multiple components that ensure motion transmission, shafts alignment and smooth rotation [10]. Theirdynamic and stochastic behavior makes them susceptible to various defects, many of which can lead to production line shutdown or safety hazards. Consequently, fault diagnosis and prognosis have become essential research areas aimed at detecting defects early and estimating remaining useful live to avoid unnecessary part replacement while improving machines availability and reliability. Modern diagnostic and prognostic systems are therefore designed around real-time monitoring and analysis of dynamic behavior [11, 12].

Recent development in diagnostic techniques for rotating machines have been leveraged measurement of noise vibrations, electrical current and temperature. However, some approachesremain limited detecting emerging faultswhere weak fault signatures are masked by high noise levels or environment interferences.Other require expensive toolssuch as infrared cameras. Among these, Vibration signal analysis remained the most effective methodfor rotating machines fault diagnosis, as vibration signalsreflect the system's dynamic state. Faultstypically manifest as increased vibration levels at specific characteristic frequencies, making their monitoring a priority.

The accuracy of vibration-based diagnosis depends heavily on the signal processing technique used. Common approaches includetime-domain analysis-such as crest factor, RMS value, kurtosis, and envelope analysis. In frequency-domain analysis, primarily using spectral analysis. By comparing measured vibration data with reference value, engineers can detect abnormalities and pinpoint malfunctioning components. Ultimately, vibration analysis remains one of the most powerful tools for evaluating the health of rotating machinery and ensuring reliable operation [13, 14].

2. Materials and methodology

In this study, we adopt vibration analysis as the primary diagnostic tool, given its proven effectiveness in condition-based maintenance (CBM) for rotating machinery. Vibration analysis is widely recognized for its ability to detect a wide range of mechanical faults—such as imbalance, misalignment, bearing defects, and gear wear—often at an early stage, before they lead to severe damage or costly downtime.

The condition-based approach differs from corrective maintenance in that it relies on systematic inspection and evaluation of equipment condition prior to making repair decisions. This strategy minimizes unnecessary interventions while maximizing the operational availability of critical assets. It is generally structured into two fundamental stages:

1. Monitoring – Continuous or periodic measurement of relevant parameters (e.g., vibration velocity, acceleration, displacement) to track the machine's health over time.
2. Diagnosis – Interpretation of monitoring data to identify the type, location, and severity of any detected anomalies.

In some cases, a third stage—prognosis—is integrated, aiming to estimate the Remaining Useful Life (RUL) of the machine or its components, thereby allowing optimized maintenance planning.

The methodological framework applied in this work is illustrated in Figure 1, which presents the sequence from monitoring to diagnosis, and, where applicable, to prognosis, forming a closed loop for continuous improvement of maintenance practices.

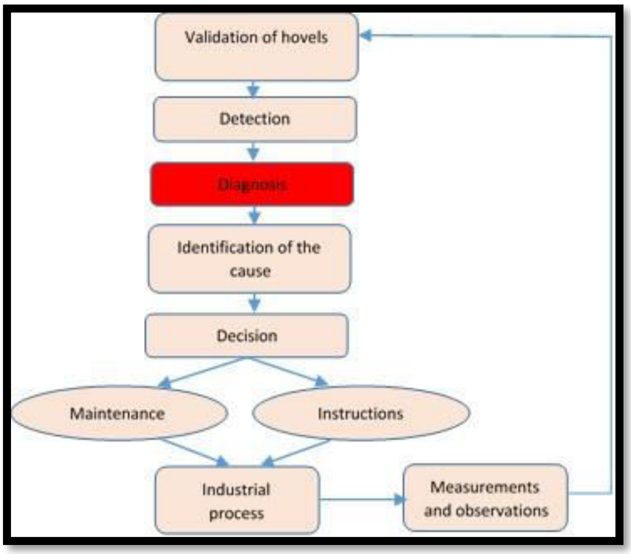

Fig. 1Following steps for diagnosing

2.1. Measurement and Diagnostic Equipment

Vibration measurements were conducted using triaxial accelerometers capable of detecting a broad frequency spectrum, allowing for the capture of both low-frequency structural vibrations and high-frequency bearing-related faults. The sensors were mounted magnetically or via threaded studs at strategic locations, such as bearing housings and gearbox casings, to ensure optimal signal transmission.

A portable vibration data collector equipped with Fast Fourier Transform (FFT) capabilities was employed to acquire and store the vibration signals. Acquisition parameters (sampling rate, resolution, and frequency range) were selected in accordance with ISO 10816 and ISO 13373 standards ensuring the reliability and comparability of results.

The vibration analysis equipment used in this diagnosis consists mainly of (Figure 2):

- ✓ VIB SCANER (VIB 5.420) analyzer/collector: Portable device for vibrations measurement.
- ✓ Accelerometer: Sensors for capturing vibration readings during operation.
- ✓ OMNITREND vibration analysis software: Utilized to process signals from different types of vibrations.

Figure 2 illustrate the VIB SCANER device. Automatic alarms were configured for each equipment unit or sub-equipment to facilitate anomaly detection. The rotary kiln is equipment with several automatic alarms connected to the control room, which provide real-time information on temperature, pressure and vibration levels via the OMNITREND software.

Fig. 2 VIB SCANER device

2.2. Measured Parameters

The primary vibration parameters monitored include:

- ✓ Overall RMS vibration velocity (mm/s) – Used as a global indicator of machine condition.
- ✓ Acceleration (g) – Particularly useful for detecting high-frequency faults such as bearing defects.
- ✓ Displacement (μm) – Used to assess low-frequency phenomena such as misalignment orimbalance.

2.3. Signal Processing and Analysis

The vibration data underwent frequency-domain analysis:Using FFT to identify characteristic fault frequencies associated with bearings, gears, and unbalance, enabling precise fault diagnosis.

The diagnostic process involved comparing the measured vibration signatures against reference spectra for the specific machine type. Any deviations beyond standard thresholds were flagged for further inspection and possible maintenance intervention.

3. Cement rotary kiln

3.1 Description

The cement rotary kiln is the central and most critical piece of equipment in the cement production line (Figure 3). It is a pyroprocessing unit responsible for the calcination of raw materials into clinker, a process that determines the quality, efficiency, and stability of cement production. Operating at the highest temperature in the process, the kiln typically reaches 1400–1450 °C for material calcination, while the flame temperature inside may rise to 1600–1800 °C or even higher [16, 15].

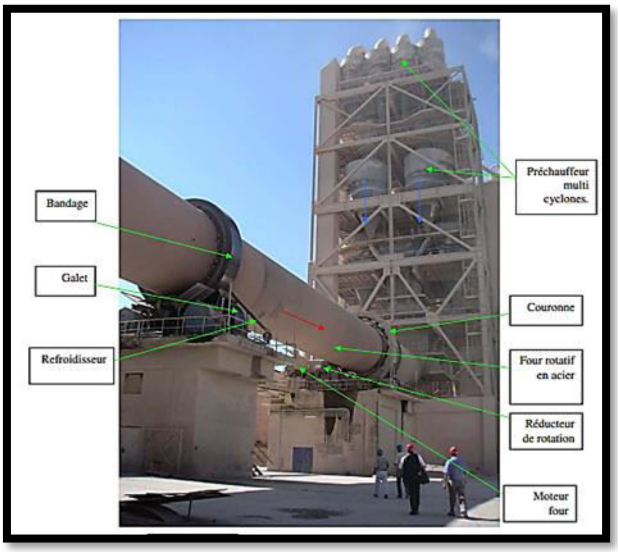

Fig. 3 Cement rotary kiln: on-site view [website Power Cement] [17]

To protect the kiln shell and reduce surface heat losses, the interior is lined with refractory masonry. This lining provides essential thermal insulation but also increases the structural load on the kiln. In the firing zone, the kiln shell is designed with a certain thickness to withstand extreme thermal and mechanical stresses, which further ads to the overall load. The reliability of the rotary kiln depends heavily on the design, quality, and maintenance of these refractory linings, as any deterioration can lead to significant operational disruptions and costly downtime.

3.2 Rotary Kiln Parts

A cement rotary kiln is composed of several key components, each playing a vital role in its operation and durability (Figure 4):

1. Kiln Shell – The large cylindrical steel structure that forms the body of the kiln, designed to withstand high mechanical loads and thermal stresses.
2. Refractory Lining – The heat-resistant brick or castable material inside the kiln that provides thermal insulation and protects the steel shell from extreme temperatures.

3. Support Rollers and Bearings – Mechanical supports that allow the kiln to rotate smoothly and bear the heavy load of the structure and its contents.

4. Girth Gear and Drive System – The mechanical assembly responsible for rotating the kiln at a controlled speed.

5. Seals – Installed at the inlet and outlet ends to minimize heat loss and prevent unwanted air infiltration.

6. Burner – The fuel injection system located at the kiln's hot end, responsible for generating the flame and maintaining required process temperatures.

7. Inlet and Outlet Zones – Sections where raw meal enters and clinker exits; these areas require special attention due to variations in temperature and mechanical stress.

A proper understanding of these components and their interactions is essential for ensuring reliable kiln performance, minimizing downtime, and extending the equipment's operational life.

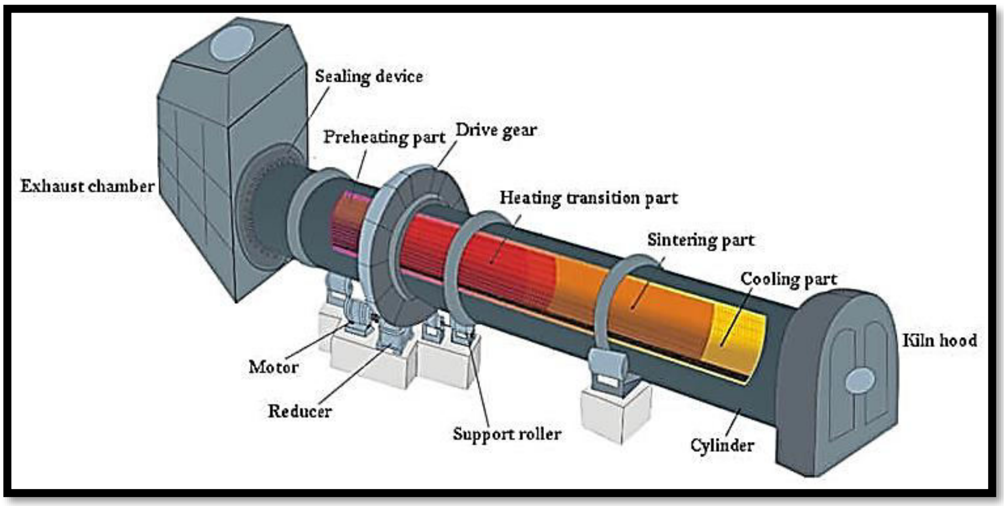

Fig. 4 Rotary kilndiagram [17]

4. Experimental results

4.1. Functional Analysis

The first step in the analysis involves identifying the external environment and clearly defining the operational requirements of the rotary kiln. Tools such as the Octopus diagram (or intersections graph) are often used for this purpose.In this diagram:

- The system (rotary kiln) is positioned at the center.

- External environment elements (operators, raw materials, fuel supply, control systems, structural supports,etc.) are placed around it.

- The functional relationships are represented as connections:

- FPi – primaryfunctional services provided by the kiln.
- FCi – functionalconstraints or services required from the environment.

This visual representation helps define the system's functional boundaries and identify possible sources of malfunction. The general structure of such a diagram is illustrated in Figure 5 [18].

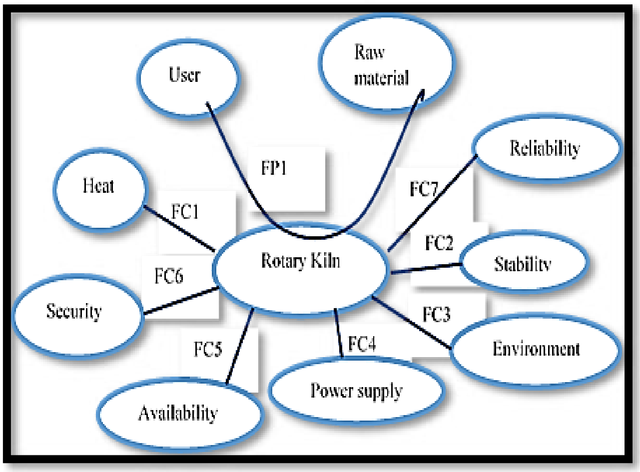

Fig. 5 Structure of an octopus diagram

FP1-Enable the user to produce clinker.
FC1-Ensure optimal reliability
FC2-Maintain stable kiln rotation
FC3-Minimize the emission of polluting gases
FC4-Power the kiln using electrical energy
FC5-Guarantee high plant availability
FC6-Ensure proper kiln operation
FC7-Generate the required heat through coal combustion

4.2 Dysfunctional Analysis (FMECA)

The dysfunctional analysis represents the second phase of the adopted methodology for acquiring in-depth system knowledge. Its objectives are to:

- ✓ Identifypotentialfailuresthat may affect the system and determine their causes.
- ✓ Assess the criticality of each failure.
- ✓ Guide the selection of the most appropriate maintenance strategy (preventive, predictive, or corrective).

This step focuses on malfunctions that could compromise the operational mission of the rotary kiln. It is implemented through the Failure Modes, Effects, and Criticality Analysis (FMECA), which is based on:

- A thorough understanding of the system and its environment (from the functional analysis).

- Operational feedback, including breakdown history and technical intervention records.

The analysis targets the most critical components and regions of the kiln, as these areas represent the highest operational risk.

To enhance the identification of maintenance priorities, the FMECA was extended to calculate a Risk Priority Number (RPN) for each component of the rotary kiln system [18]:

RPN = Severity (S) × Failure Likelihood (F) × Detection (D)   (1)

This approach enables the ranking of components based on their criticality, facilitating the planning of preventive and corrective maintenance actions. By combining the ranges for risk likelihood, risk severity, and detectability, it is possible to classify the acceptability level of each potential failure mode.

- **Synthesis of FMECA analysis :**

The rotary kilnisdivided in to three main Subsystems : Transmission System ;Supporting System ; Sealing System. Table 1presentssummary of the number of failures for eachsubsystem's components categorized according to the criticalitylevelsdeterminedin the FMECAanalysis. The resultsindicatethat the *supportingsystem*is the mostcriticalsubsystem, as faultswithinitconstitute a major cause of rotary kiln breakdowns and cansignificantly impact overalloperationalreliability.

Table 1.Summary of subsystem failure analysis

Subsystem	**Failureswith high criticality**	**Failureswith acceptable criticality**	**Failures with negligible criticality**
Transmission System	1	1	5
Supporting System	4	6	10
Sealing System	2	2	6

Action plan :

- *RPN* ≤12-High acceptability: No immediate action required.
- 12< *RPN* ≤24-Borderline acceptability : implementpreventive maintenance.
- *RPN*>24-Not acceptable : immediateriskreductionmeasuresrequired.

From figure 6, it can be observed that the support roller in the *supportingsystem* has the highest RPN value (48), making it the most critical component to prioritize in the maintenance plan.

According to Zheng et al. [19] and Gebhart&Stutz [20], support roller faults are primarycaused by the kilncrank, whichgenerated by the internal thermal processes, within the rotary kiln. Over long-termoperation, deformation of the kiln profile canoccurleading to misalignment between the geometric center and the rotation axis. thismisalignment causes eccentricity in the cylinder cross-section. theresultingdynamicloadfromthiseccentricityinduce vibrations in support rollers.

The ‘snowballeffect’ in the kilncylindercanfurtherintensifythese vibrations. As described by Rusinski et al. [21], during the operation, materialscanform a ball-like mass thatrotatesalong the kiln axis. When the weight of the snowballexceeds the adhesive forces between the kilncoating and the snowballdetachesfrom the coating. Under extreme thermal conditions, thisprocesscan lead to severloadunbalances of the support rollers, exacerbating wear and increasing the risk of failures.

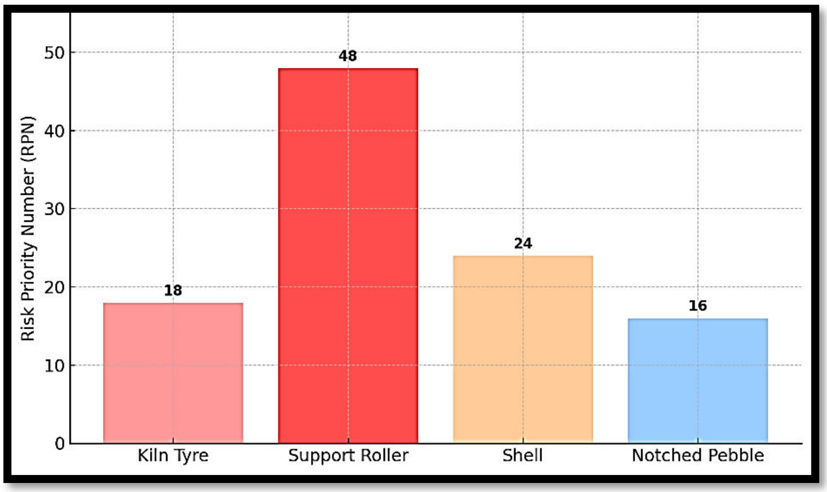

Fig.6 Highest RPN per Subsystem-Rotary Kiln FMECA

An excerpt from the FMEAC is presented in Table 2. It includes only the elements for which the calculated criticality is greater than six (6) and which therefore require particular attention.

The FMECA results highlight that within the supporting system, the support roller presents the highest Risk Priority Number (RPN = 48), making it the most critical component requiring immediate attention in the maintenance plan. High RPN values are also observed for bending exceeding limits (RPN = 32) and shell deformation issues (RPN = 24), indicating significant potential impacts on operational reliability. The primary causes include fatigue, excessive loads, crankshaft effects, and thermal deformation, which can lead to severe mechanical failures if not addressed. Preventive measures such as continuous monitoring of kiln deformation, regular NDT inspections, and systematic preventive maintenance are essential to mitigate these risks and improve the system’s reliability and lifespan.

Table 2. FMECA of Supporting System

	Failure Mode Effect and CriticalityAnalysisWorksheet								FMECA Machine
Subsystem	Function	Failure mode	Failure cause	Effets	Criticality				Corrective actions
					F	S	D	RP	

								N	
Kiltyre	Transfer the gravity of the cylinder on the supporting roller	Cracking	- Poortyre /roller contact - Excessive wear - Oscillation	- Resistanceweakening. - Kilntyredamaged or evenbroken.	1	3	3	9	Visual inspection
		Incorrect negative slip	- Increasetemperaturethrough roller set -Poor cold startmonitoring	-Permanent deformation -Refractory bricksdegradation	2	3	3	18	Continuous monitoring of slip (MKM) and ovality
		Incorrect positive slip	- Insufficient plates compensation - Increasedtemperature	-Ovalization -brick deterioration	3	3	2	18	Continuous monitoring of slip (MKM) and ovality
		Oscillation	- Incorrect cylindricity	- Wear of contact surfaces	1	3	3	9	Geometricalcontrol
		Wear plates	- Worncompensation plates - Increased	- Acceleration wear	1	2	3	6	Inspectingduringkilnshutdown

			clearance						
		ThrustblockBreakage	- Cracking - Oscillation of Kilntyre	- Tyredetachment	1	3	3	9	NDT duringkiln shutdown
Support roller	Support and fix the cylinder	Fragile breakup	- Fatigue - Crankshafteffect - Rotational flexion - Excessive load	- Degradedproperties - Weakenedresistance -Breakage	4	3	4	48	Roller replacement Performance ; Improvement systematicpreventive maintenance
		Bending exceeding	- High load - Crankshafteffect - Oscillatingtyre	-Cracking	2	4	4	32	Kilndeformation control
		High bearingtemperature	-High shelltemperature - Poorcooling -Poor lubrication - Friction	- Bearingdegradation	3	4	1	12	Regular temperaturemonitoring
		Axis inclination	- Incorrect setting -	-Increased surface wear	1	2	3	6	IDM duringkiln shutdown

			Overload at contact area						
		Cylindricity Defect	-Uneven wear	-Increased surface wear	1	2	3	6	Lead wire wear control
		Roller surface Chipping	- Exceeding service life	-Risk of tyre damage	1	2	2	4	
			- Excess Hertz pressure	-Risk of tyre damage	1	2	2	4	
Shell	Gas and Air Conduction	Deformation	- Bending - Uneven temperature - Falling bricks - Crusting	- Roller cracking - Shaftbending - Brick fall	2	3	4	24	Kilnshell laser measurment ; Temperaturemonitoring
		Ovalization	- Excessive clearance	- Bricks damage - Longitudinal cracking - Shell damage	2	4	3	24	Ovality control
		Circular cracking	- Welding damage - Bad alignment - Corrosion	- Shell breakage - Hightemperature.leakage	2	4	3	24	NDT duringkilnshutdown
		longitudinal cracking	- Blocks welding -	-Cracking -Reduced bricklife	2	3	3	18	NDT+temperature monitoring

			Excessive loadtyre.						
		Axis deviation	-Wrong roller setting - Plastic deformation	-Kilnlowering	1	2	3	6	Alignment check
		Crankshafteffect	- Hot spots	- Shaftbending - Roller breakagerisk	2	4	3	24	Temperaturemonitoring ;Shaftdeflectionmonitoring
NotchedPebble	Motion tube	High coolerexhaustgastemperature	- Excessive rotation	- Poor clinker cooling	2	2	4	16	Inspection ; Lubrication ; Backup

4.3 Off-Line Monitoring of the Rotary Kiln (Vibration Diagnosis)

Due to its high operating temperature, heavy load, high rotational speed, and considerable length, the rotary kiln is highly susceptible to vibrations. These vibrations can vary significantly in both magnitude and nature. The following section briefly outlines the main sources of vibration in the rotary kiln.

4.3.1 Selection of Measurement Points

When performing measurements aimed at detecting damage indicators, careful selection of the measurement points is crucial. Since machine operation is closely related to its degradation, special emphasis is placed on the bearings, as they serve as the primary transmission path for vibrations.

To gain a better understanding of the observed issues and to identify the defective components—thus enabling targeted maintenance actions—additional points were chosen in areas most likely to yield valuable insights into the system's vibrational behavior.

In total, nine measurement points were configured to assess the kiln's operational behavior, as illustrated in Figure 7.

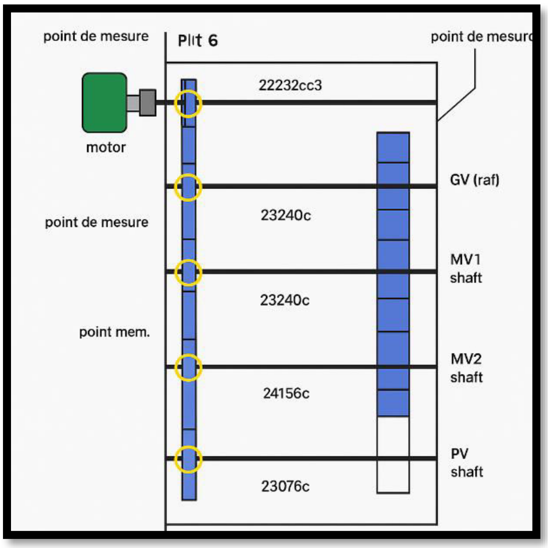

Fig. 7Position of adopted measurement points

4.3.2 Calculation of Kinematic Data

Calculating the kinematic parameters of the equipment is an essential step in defining its vibration signature. This signature serves as the fundamental reference for vibration monitoring, enabling the identification of characteristic defect frequencies and the determination of acceptable amplitude thresholds for each component. These parameters make it possible to pinpoint the frequencies at which anomalies are likely to appear and to establish both the minimum and maximum permissible vibration levels (see Tables 3 and 4).

Table 3. Gear Fault Frequencies

Ref.	**Teeth (t)**	**N (RPM)**	**Fc (Hz)**	**Fp (Hz)**
Z1 = 24	1200	20	480	
Z2 = 104	276.92	4.61	480	
Motor	Z3 = 23	276.92	4.61	106.14
	Z4 = 116	54.90	0.915	106.14
	Z5 = 22	54.90	0.915	20.13
Pinion	Z6 = 100	12.07	0.20	20.13
	Z7 = 34	12.07	0.20	6.85
Gear	Z8 = 208	1.97	0.03	6.85

Table 4. Bearing Fault Frequencies

Ref.	**Bearing**	**fbi (Hz)**	**fbe (Hz)**	**fe (Hz)**	**fc (Hz)**
GV shaft	22232cc3	216.40	163.44	138.80	8.60
	23040cc3	275.70	224.24	189.60	8.98
MV1 shaft	22240k	50.03	37.68	31.67	1.98
	23240c	49.87	37.84	32.52	1.99
MV2 shaft	24156c	11.26	8.90	7.46	0.40
	23156c	11.27	8.89	7.51	0.43
PV shaft	23076c	3.35	8.90	2.42	0.092
	23984c	4.158	3.642	2.986	0.093

Legend:

- fbi – Internal ring frequency
- fbe – External ring frequency
- fe – Rolling element frequency
- fc – Cage frequency

4.3.3 Spectral Analysis

Spectral analysis enables fault monitoring by measuring the amplitude of specific spectrum lines corresponding to the target defect. A measurement campaign was conducted on 16 April 2023 to perform spectral analysis, and the resulting vibration spectra are presented in the figures below. Only the most significant results are discussed here.

a) Motor SHF 355 VL1

At the fixed motor bearing, the spectra measured in the horizontal direction—both in speed and acceleration—are shown in Figures 8 and 9.Both spectra indicate an unbalance fault at 18.88 Hz with a speed amplitude of 0.51 mm/s. According to the ISO 10816-3 vibration threshold table, this value is within the acceptable range.

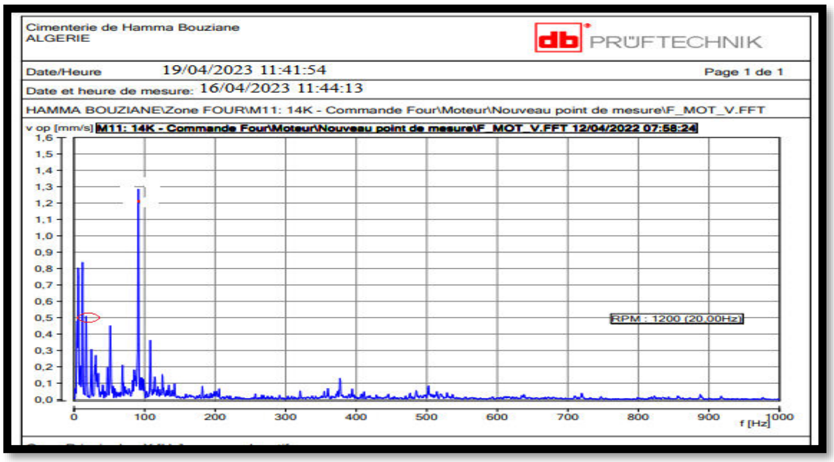

Fig. 8 Velocity spectrum

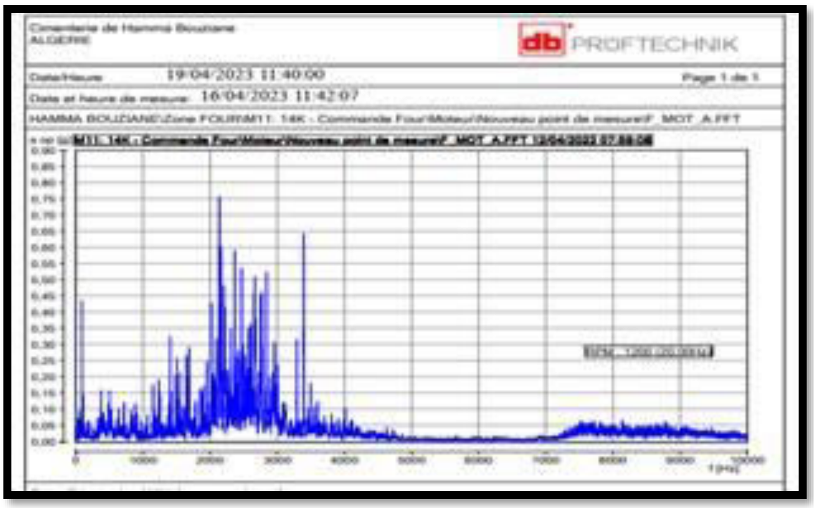

Fig. 9 Accelerating spectrum

b) Main Reducer

Eight measurement points were configured on the main reducer, which consists of four shafts (GV, MV1, MV2, and PV), each with two measuring points.

- GV shaft (P1 and P2)

The spectrum at P1 (motor side, Figure 10) shows two dominant peaks: a meshing fault at 426 Hz (1.09 mm/s) and an unbalance at 17.98 Hz (1.08 mm/s). Both values are negligible per ISO 10816-3. The vibration levels at P2 (pinion side, Figure 11) are similar to those at P1.

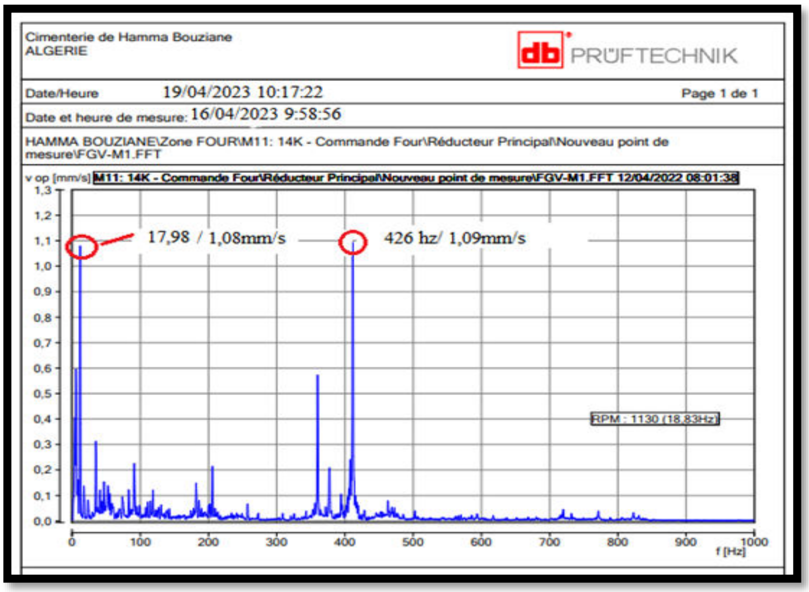

Fig. 10 Velocity spectrum (P1)

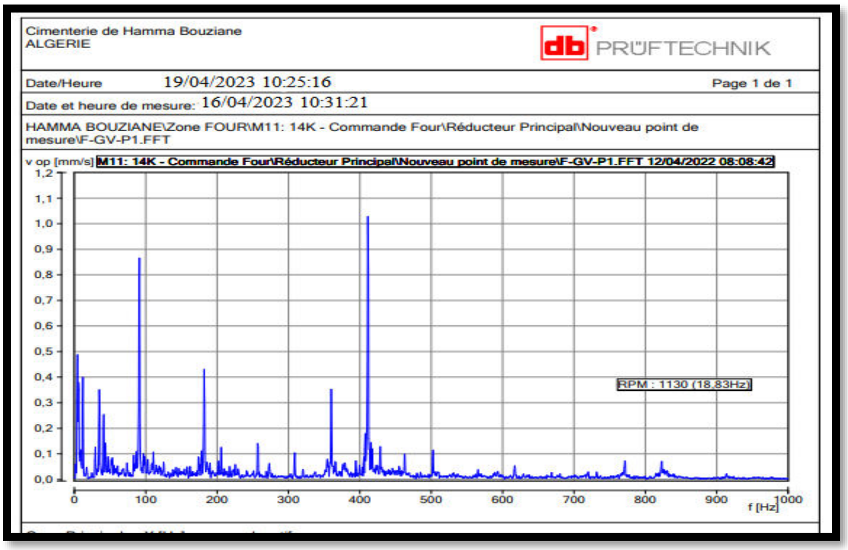

Fig. 11 Velocity spectrum (P2)

- MV1 shaft (P3 and P4)

Speed vibration measurements at the input (motor side) and output (pinion side) are shown in Figures 12 and 13. The amplitudes are unstable, indicating an unbalance fault at 4.38 Hz, with speed increasing from 0.31 mm/s to 0.45 mm/s—still within acceptable limits.

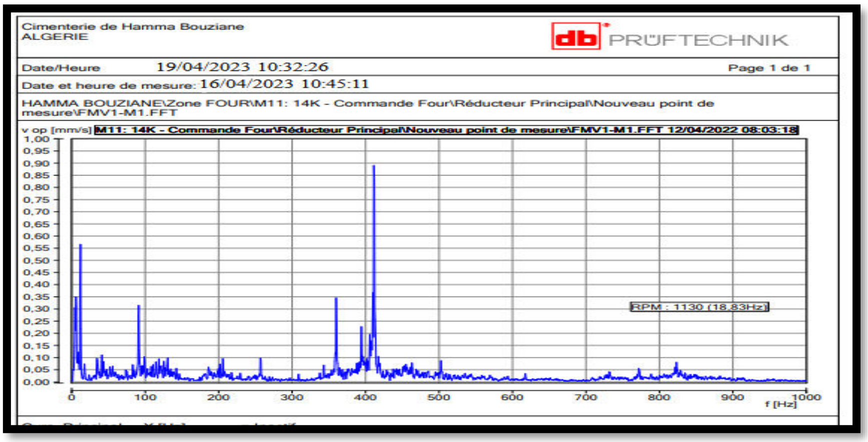

Fig. 12 Velocity spectrum (P 3)

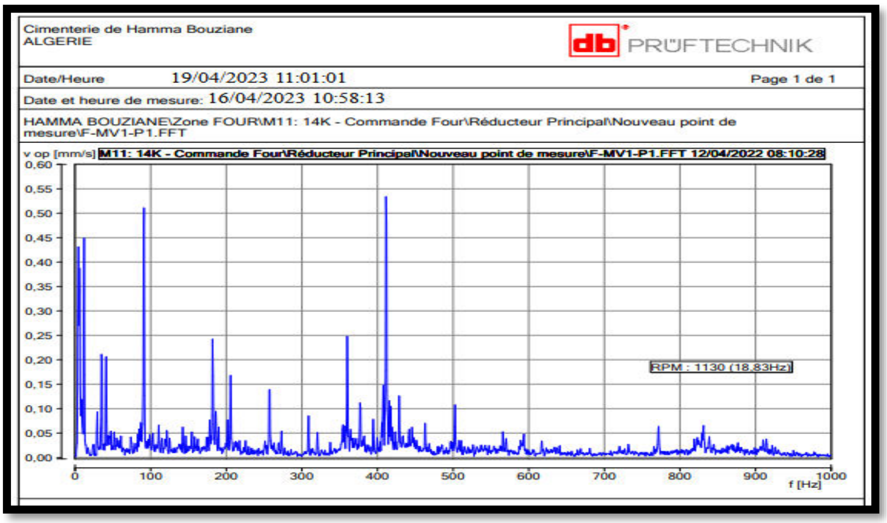

Fig. 13 Velocity spectrum (P4)

- MV2 shaft (P5 and P6)

At P5 (Figure 14), a meshing fault between MV2 and PV is observed at 17.66 Hz with an amplitude of 1.25 mm/s (good condition per ISO 10816-3). At P6 (Figure 15), a similar fault is detected at 17.3 Hz with 0.52 mm/s, also acceptable.

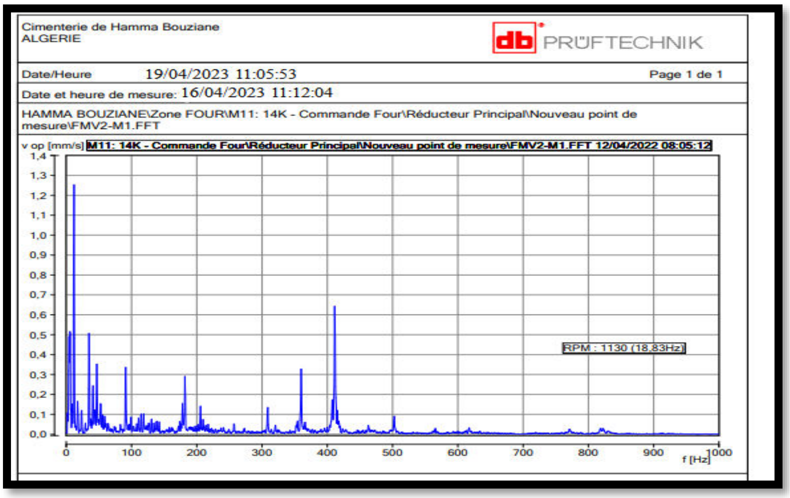

Fig. 14 Velocity spectrum (P5)

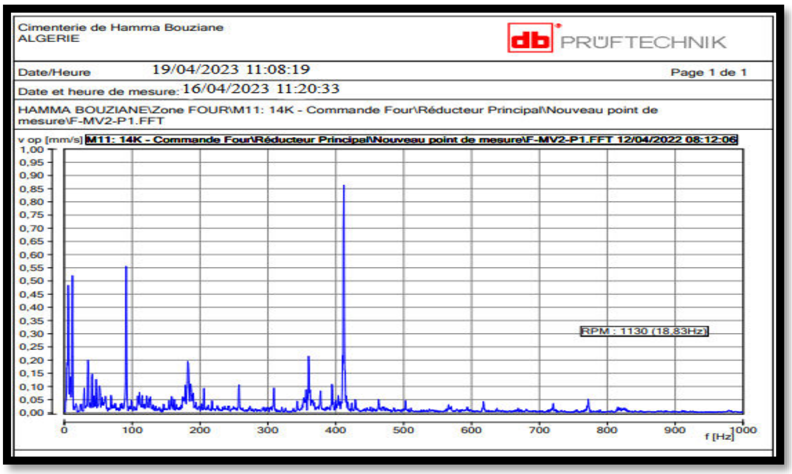

Fig. 15 Velocity spectrum (P6)

- PV shaft (Bearings 7 and 8)

Figures 16 and 17 reveal a peak at 5.63 Hz with an amplitude of 0.7 mm/s. Both bearings are within the acceptable vibration threshold.

From these observations, the main reducer is considered to be in good operating condition.

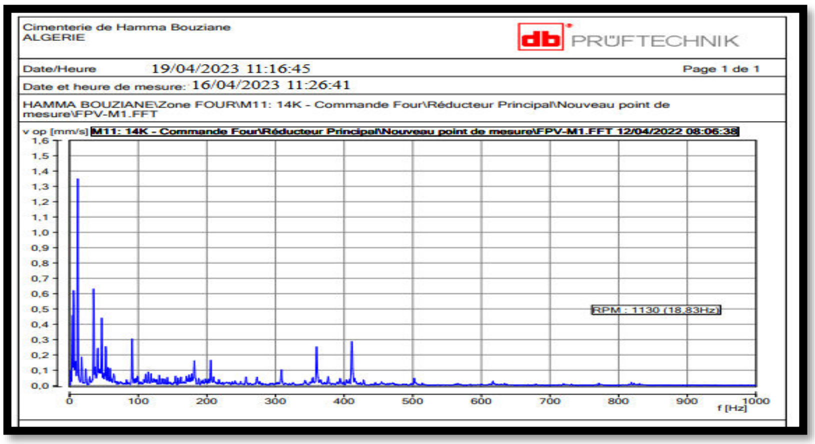

Fig. 16 Velocity spectrum (P7)

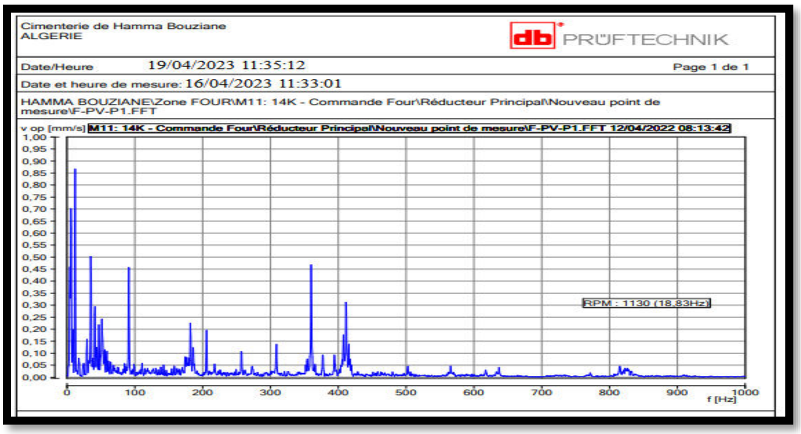

Fig. 17Velocity spectrum (P8)

c) Pinion Bearing

Figures 18 and 19 present the speed and acceleration spectra for the free bearing of the pinion on the PV shaft (horizontal direction). Peaks at 6.25 Hz are observed, with a speed amplitude of 0.32 mm/s and acceleration of 1.23 g, indicating a minor meshing fault within acceptable limits.

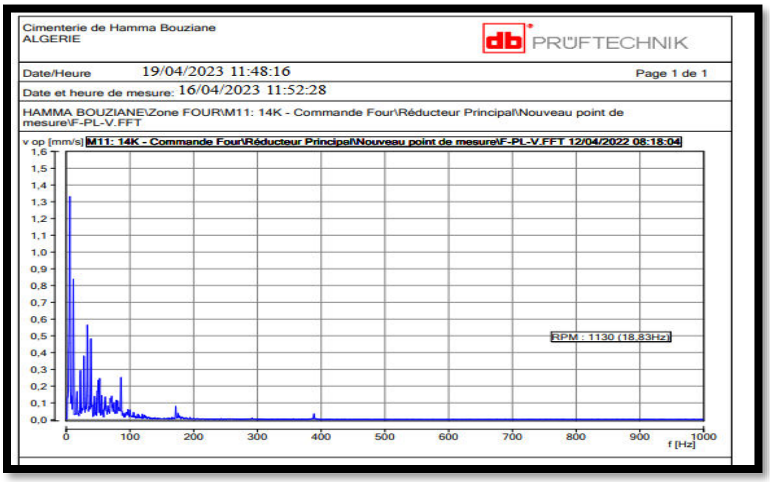

Fig. 18 Velocity spectrum (P9)

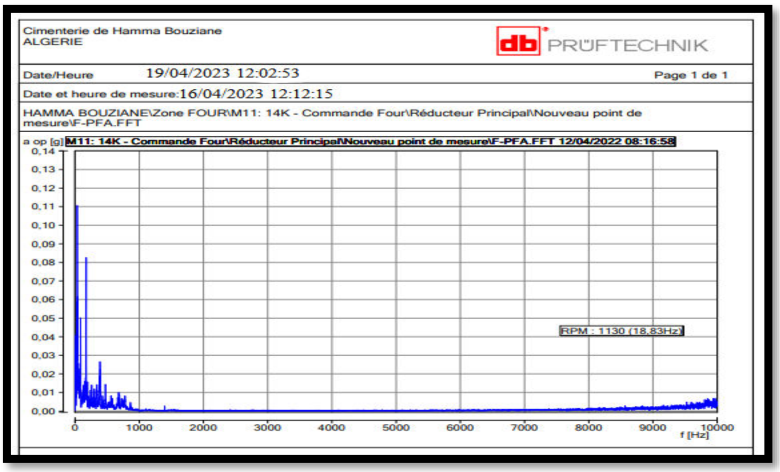

Fig. 19Accelerating spectrum (P9)

Spectral analysis of the motor, reducer, and associated components revealed unbalance faults in the motor shaft (GV) and reducer shafts (MV2 and PV), as well as gear-related faults in the main reducer. Notably, bearing defect frequencies were absent in the spectra for P3 and P4, which aligns with the fact that these bearings were replaced in December 2021.

5. Conclusion

An FMECA was performed on the rotary kiln system at three main levels: the supporting system, the sealing system, and the transmission system. This analysis enabled a structured ranking of failure modes according to their Risk Priority Number (RPN), providing a clear basis for criticality classification. The prioritization of the most critical components offers targeted opportunities to enhance system reliability and optimize maintenance planning.

The integration of vibration analysis proved highly effective in delivering accurate technical diagnoses, enabling the rapid detection of defective components, and supporting systematic inspection and maintenance of every kiln subsystem. Since each component plays a vital role and can induce failures in others, identifying and addressing critical points is essential.

By combining the FMECA results with vibration analysis, we were able to clearly pinpoint potential malfunctions, highlight high-risk areas, and propose targeted maintenance actions aimed at reducing criticality, improving reliability, and extending the operational lifespan of the rotary kiln system.

Statements & Declarations

Funding: The research presented in the manuscript didnot receive any external funding.

Competing Interests: The author reported no potential conflict of interest.

Author Contributions: Conceptualization: L.B.; Methodology: L.B.; Data collection: L.B.; Research and writing, L.B.; Supervision: R.C.; Review: R.C.

References:

1. *Gomaa, A. H. (2025). Maintenance 4.0: Optimizing Asset Integrity and Reliability in Modern Manufacturing. Int. J. Inven. Eng. Sci.(IJIES) 12: 18-26. www.ijies.org*
2. *Ramere, M. D., &Laseinde, O. T. (2021). Optimization of condition-based maintenance strategy prediction for aging automotive industrial equipment using FMEA. Procedia Computer Science 180: 229-238. www.sciencedirect.com*
3. *Hellas, M. S., Chaib, R., Nettour, D., &Zerrouki, H. (2024). A new approach proposal for ensuring security engineering through barrier and operational quantitative risk analysis (BOQRA). Journal of Loss Prevention in the Process Industries 91: 105390. www.sciencedirect.com*
4. *Khan, A., Gupta, S., & Gupta, S. K. (2020) Multi-hazard disaster studies: Monitoring, detection, recovery, and management, based on emerging technologies and optimal techniques. International journal of disaster risk reduction 47: 101642. (www.sciencedirect.com)*
5. *Lei, Y., Li, N., Guo, L., Li, N., Yan, T., & Lin, J. (2018).Machinery health prognostics: A system a ticre view from data acquisition to RUL prediction. Mechanical systems and signal processing104 : 799-834.(www.sciencedirect.com)*
6. *Jiang, Y., Yin, S., Dong, J., &Kaynak, O. (2020). A review on soft sensors for monitoring, control, and optimization of industrial processes. IEEE Sensors Journal21(11) : 12868-12881.(ieeexplore.ieee.org)*
7. *Bouyaya, L., Chaib, R., & Verzea, I. (2022). Contribution to the improvement of pumping system reliability. Case study: Beni-Haroun water pump station,*

Algeria. Acta Technica Napocensisseries: Applied Mathematics Mechanics And Engineering 65(2).(atna-mam.utcluj.ro)

8. *Bouyaya, L., &Chaib, R. (2022). Maintenance and Reliability of a MotorPump: A Case Study. International Journal of Performability Engineering 18(8) : 559.(www.ijpe-online.com)*
9. *Babak, V. P., Babak, S. V., Myslovych, M. V., Zaporozhets, A. O., &Zvaritch, V. M. (2020). Technical provision of diagnostic systems. In Diagnostic systems for energyequipments 91-133. Cham: Springer International Publishing.(link.springer.com)*
10. *Nath, A. G., Udmale, S. S., & Singh, S. K. (2021). Role of artificial intelligence in rotor fault diagnosis: A comprehensive review. Artificial Intelligence Review54 : 2609-2668.(link.springer.com)*
11. *Fu, C., Sinou, J. J., Zhu, W., Lu, K., & Yang, Y. (2023).A state-of-the-art review on uncertainty analysis of rotor systems. Mechanical Systems and Signal Processing 183 : 109619.(www.sciencedirect.com)*
12. *Malla, C., &Panigrahi, I. (2019). Review of condition monitoring of rolling element bearing using vibration analysis and other techniques. Journal of Vibration Engineering & Technologies 7 : 407-414.(link.springer.com)*
13. *Choudhary, A., Goyal, D., Shimi, S. L., &Akula, A. (2019). Condition monitoring and fault diagnosis of induction motors: A review. Archives of ComputationalMethods in Engineering 26 : 1221-1238.(link.springer.com)*
14. *Chaïb, R., Taleb, M., Benidir, M., Verzea, I., &Bellaouar, A. (2014).Failure:a source of progress in maintenance and design. Physics Procedia 55 : 185-191.(www.sciencedirect.com)*
15. *Kolagar, M., Hosseini, S. M. H., &Felegari, R. (2021).Developing a new BWM-based GMAFMA approach for evaluation of potentialrisks and failure modes in production processes. International Journal of Quality&Reliability Management 38(1) : 273-295.(www.emerald.com)*
16. *Hasan, S., Sahiri, E., Suprayitno, S., &Hartanto, E. T. (2019).Analysis Of Determining Critical Components Using FMECA Method In SeawaterPump Of Diesel Generator Caterpillar 3412. Journal Asro 10(3) : 124-130.(asro-algerie.com)*
17. *Zheng, K., Zhang, Y., & Li, T. (2016).Faultdiagnosis for supporting rollers of the rotary kilnusing the dynamic model and empirical mode decomposition. Mechanics 22(3) : 198-205.mechanika.ktu.lt*
18. *Gebhart, W. M., &Stutz, T. (2007).Process Know-how-Routine Support Roller Shaft Deflection Measurements- Surprising Results. ZKG International 60(7) : 50-55.zkginternational.com*
19. *Rusinski, E., Stamboliska, Z., &Moczko, P. (2013). Proactive control system of condition of low-speed cementmachinery. Automation in Construction 31 : 313-324.www.sciencedirect.com*