The 13th ISAV2023 International Conference on Acoustics and Vibration
20, 21 Dec 2023 Tehran - Iran
Iranian Society of Acoustics and Vibration

Vibration Analysis for Fault Diagnosis in Multi-Stage Centrifugal Pumps: A Case Study at Khatun Abad Copper Complex

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Abstract

High-pressure multistage centrifugal pumps are among the widely used equipment in various industries, efficiently transporting fluids over long distances or through systems with substantial pressure differentials. Due to their crucial role, it is imperative that regular condition monitoring be performed. Condition monitoring involves various methodologies, one of which is vibration condition monitoring. After vibration condition monitoring of the 7-stage centrifugal pump at the Khatun Abad copper complex, remarkably high levels of vertical and horizontal vibration amplitudes of the bearings were observed. Hence, this study aims at the fault diagnosis for the multi-stage centrifugal pump at the Khatun Abad copper complex using vibration analysis. To achieve this end, data collection was performed using a vibrometer and accelerometer vibration probe, subsequently followed by a thorough examination of the results. Examining the vibration frequency spectrum within the bearings revealed the dominance of particular harmonics, distinguished by varying amplitudes across different directional components. Therefore, a thorough examination of the fault's underlying cause was conducted, taking into account both hydrodynamic and mechanical aspects. The deduction was made that the leading mechanical factor contributing to the observed vibrations is the damage or corrosion to the impeller or diffuser, resulting in an asymmetrical condition. Additionally, blockage of diffuser passages and wear ring clearance issues could also be other reasons for the mentioned vibration. Ultimately, some recommendations are proposed to address these challenges and ensure the continued optimal performance of the multi-stage centrifugal pump.

Keywords: vibration condition monitoring; frequency spectrum; fault diagnosis; high-pressure multistage centrifugal pump.

1. Introduction

High-pressure multistage centrifugal pumps are meticulously engineered to meet the exacting demands of modern industries. They play a vital role in the transport of fluids across lengthy distances or through systems with substantial pressure variations. This class of pumps comprises multiple impellers mounted on a shared shaft, with each impeller contributing to the overall increase in pressure. As the fluid progresses through each impeller stage, its kinetic energy is converted into additional pressure energy. This unique capability allows these pumps to attain the high-pressure levels fundamental for a wide array of industrial applications, including petrochemicals, oil refining, power generation, water supply, and mining industries [1], [2], [3], [4], [5].

Given the critical nature of these pumps and their critical roles, monitoring their condition is of utmost importance. Condition monitoring includes a variety of methods, one of which involves analysing vibrations as a diagnostic technique [6], [7]. There exists a multitude of issues that can impede the operation of a pump. These issues encompass a wide spectrum of operational challenges, ranging from mechanical faults to fluid-related concerns, all of which have the potential to disrupt the pump's performance and efficiency. Imbalance, for instance, is a common issue associated with centrifugal pumps and has been extensively studied [8]. For submersible pumps, the detection of a broken impeller has been explored by estimating rotational frequency using motor current signals [9]. Researchers have also explored the problem of cavitation, another issue linked to pumps [10], [11].

Vibration-related problems in centrifugal pumps, particularly high-pressure multistage centrifugal pumps, leads to considerable challenges to the safety and overall stability of their operations [12], [13], [14], [15]. Numerous factors can affect the operation of these pumps. For instance, A. Adamkowski et al. carried out research on the resonance of torsional vibrations in centrifugal pump shafts, a phenomenon attributed to cavitation erosion affecting pump impellers [16]. The resonance properties of a centrifugal pump rotor system have been examined by determining natural frequencies and critical speeds using the finite element method [17]. Moreover, A. Albraik et al. have conducted fault diagnosis of centrifugal pumps through vibration analysis [18].

In this study, we perform fault diagnosis on the multi-stage centrifugal pump at the Khatun Abad copper complex using vibration analysis. To accomplish this, we recorded the bearing's vibrations according to a periodic condition monitoring schedule using the VIBPRO V4- 2 Channels (F-max 40 kHz). This led to the observation of high-amplitude horizontal and vertical vibrations in the third bearing. Finally, we investigate the root cause of the issue and propose necessary actions to rectify the problem.

2. Test setup

Vibration condition monitoring is a vital technique employed to assess the health status of various industrial equipment. Typically, in industrial settings, vibration condition monitoring is performed according to a predetermined schedule. At the Khatun Abad copper complex, one piece of equipment under examination is the multi-stage centrifugal pump, as illustrated in Fig. 1. This equipment features four bearings, and vibration measurements were taken in three different axes (vertical, horizontal, axial) at four distinct points. To record the pump's vibrations, we utilized the VIBPRO V4- 2 Channels vibrometer (fmax = 40 kHz) in conjunction with the accelerometer vibration probe shown in Fig. 2. Additionally, you can find a summary of the pump's specifications in Table 1. According to the information in Table 1, the described pump is a 7-stage unit with a speed of 2963 rpm (49.3 Hz).

Figure 1. Pump Bearing Positions.

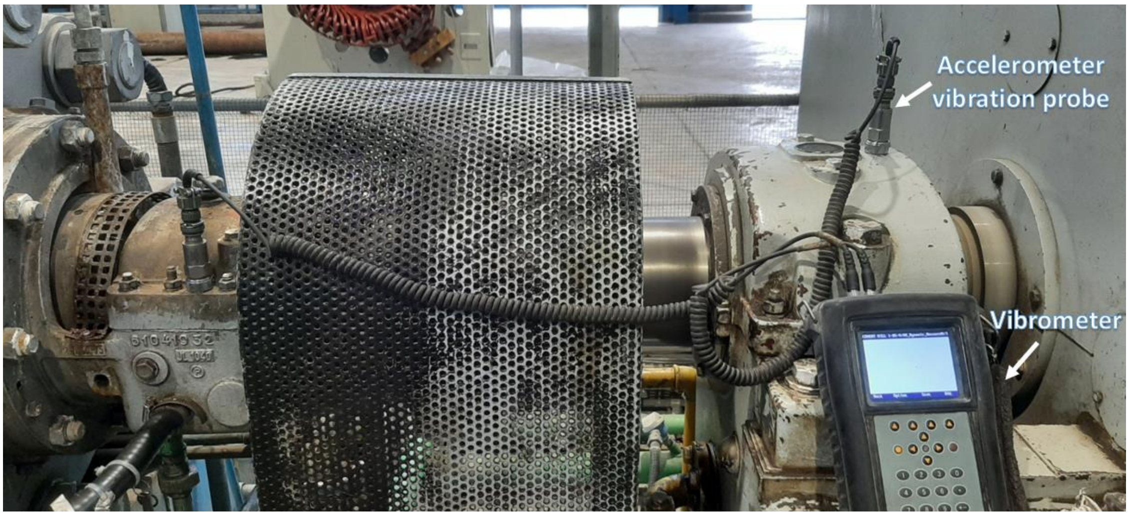


Figure 2. Test setup.

Table 1. Pump specification.

Parameter	Value
Type of pump	Centrifugal
No. of stages	7
Speed	2963 rpm (49.3 Hz)
No. of impeller blades	7
No. of diffuser vanes	8
Bearing type	Journal
Motor power	2600 kw
Coupling type	Rigid
Coupling	Gear

3. Results and discussion

In this section, a comprehensive analysis of the performance of vibration condition monitoring is undertaken. Initially, vibration condition monitoring of the pump was conducted using the aforementioned equipment. The results obtained from this monitoring are presented in Table 2. It is evident that the vertical and horizontal vibration amplitudes for bearing number 3 are exceptionally high. According to ISO 10816-7 standards, the pump falls within the third-class category. Consequently, the allowable vibration value should not exceed 3.5 for the RMS value. To illustrate, the results obtained for bearing number 3 are visualized in Fig. 3. Notably, the tenth harmonic (approximately 491 Hz) displays a prominent amplitude in both the vertical and horizontal directions, with a comparatively lower amplitude in the axial direction of bearing number 3. Additionally, it is worth noting that within this bearing, the most significant vibrations at this frequency are primarily observed in the horizontal direction. Furthermore, the frequency spectrum of the third bearing reveals the presence of the first, second, third, seventh, and tenth harmonics, each exhibiting relatively low amplitudes.

Moreover, the twice-frequency of the tenth harmonic (approximately 491 Hz) is observable in the frequency spectrum of the third bearing across all three directional components. In addition to bearing number 3, the tenth harmonic (approximately 491 Hz) is also evident in all three directional components of the frequency spectrum for the fourth bearing, albeit with a relatively low amplitude. It is worth highlighting that for this bearing, the vertical direction records the highest amplitude for the tenth harmonic.

Additionally, the frequency spectrum of the third bearing also indicates the presence of the first, second, third, seventh, and tenth harmonics, all characterized by relatively low amplitudes. In the frequency spectrum of bearing number 4, both the horizontal and axial directions display the presence of the first, second, sixth, seventh, eighth, and tenth harmonics, each marked by a low amplitude.

Table 2. Overall RMS values.

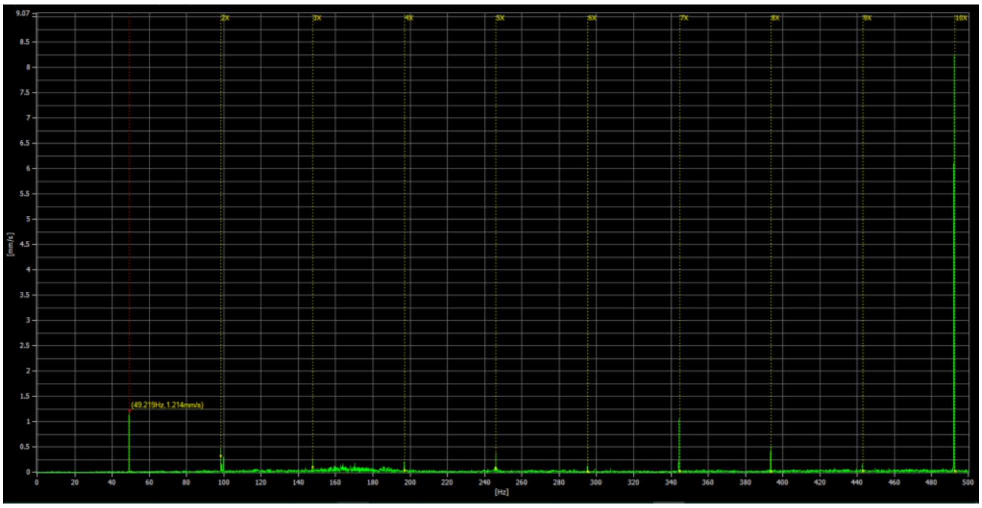
Meas.	Velocity - mm/s (2-2000 Hz)						Acceleration - g (10-10000 Hz)		
	Vertical (mm/s)		**Horizontal (mm/s)**		**Axial (mm/s)**		**Vertical (g)**	**Horizontal (g)**	**Axial (g)**
	Am.	*V.S	Am.	V.S	Am.	V.S	Am.	Am.	Am.
B1	**1.39**	**A**	**1.16**	**A**	**1.39**	**A**	**0.14**	**0.12**	**0.12**
B2	**0.96**	**A**	**1.19**	**A**	**1.91**	**A**	**0.17**	**0.16**	**0.22**
B3	**6.28**	**C**	**7.77**	**D**	**0.76**	**A**	**2.20**	**2.73**	**2.56**
B4	**2.14**	**A**	**1.04**	**A**	**0.68**	**A**	**0.81**	**0.49**	**0.90**

Equipment conditions:

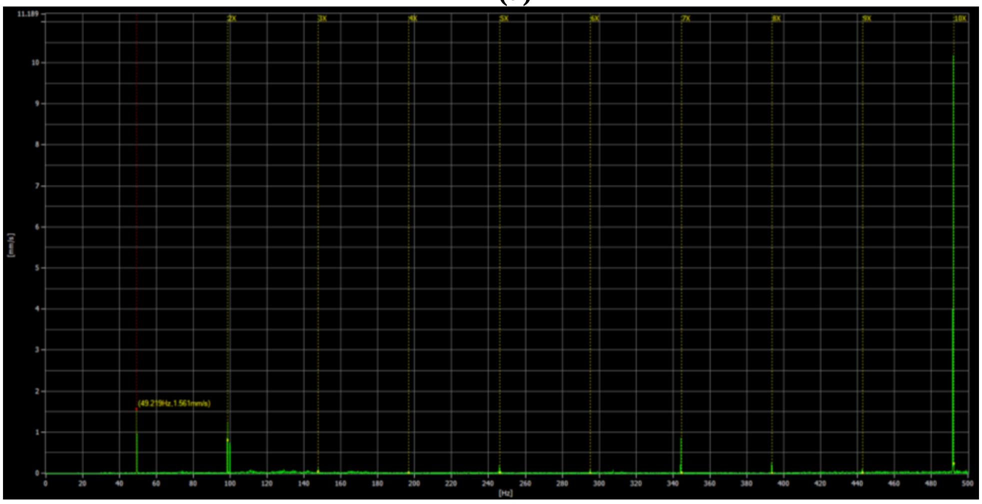
Class: I ☐ II ☐ III ☒ IV ☐

*__Vibration Severity (ISO 10816-7):__

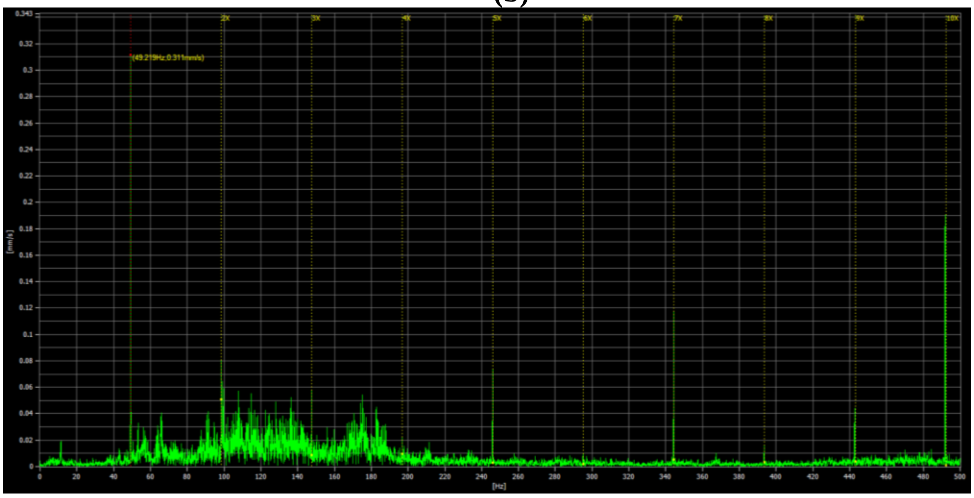
Zone	**A**	**B**	**C**	**D**
Vibration (mm/s – RMS)	**≤ 3.5**	**3.5 – 5**	**5 – 7.6**	**≥ 7.6**
	Good	Satisfactory	Unsatisfactory	Unacceptable



(a)



(b)



(c)

Figure 3. Frequency spectrum of bearing No.3; a) vertical; b) horizontal; c) axial.

4. Fault diagnosis

Following data acquisition and a comparative analysis with data obtained from similar pumps at the Khatun Abad copper complex, it is evident that all aspects observed, including the presence of the tenth harmonic in the frequency spectrum of the other pumps, remain consistent. The primary distinction lies in the amplitude of the tenth harmonic, approximately 491 Hz, which exceeds that of the other pumps and exceeds the acceptable threshold for this specific pump under study. Considering the recurring presence of the tenth harmonic in all pumps, it can be reasonably concluded that this harmonic is an inherent characteristic of pumps of this type.

However, in the case of the pump under investigation, there may have been alterations that have expanded its vibration spectrum. In multi-stage centrifugal pumps where the impeller blade count differs from that of the diffuser blades, the emergence of harmonics beyond the Blade Passing Frequency (BPF) in the pump's frequency spectrum may result from the interaction between the impeller blades and the diffuser [18], [19]. The amplification of these harmonics can originate from either mechanical or hydrodynamic sources.

4.1 Hydrodynamic factors

Hydrodynamic effects primarily stem from operational parameters, including factors such as flow rate, suction pressure, and discharge pressure. When vibration is considered as one of these operating parameters, any changes in these parameters can significantly influence vibration amplitudes. Ideally, when a pump operates within the optimal range specified in the manufacturer's catalogue, vibrations should be minimized. However, it is essential to note that based on a comparison of the performance and vibration characteristics of similar pumps with the pump under investigation, the likelihood of achieving this optimal state appears to be rather low.

4.2 Mechanical factors

The primary mechanical factor contributing significantly to these vibrations is the presence of corrosion or damage to either the impeller or the diffuser, resulting in an asymmetry within these critical components. When asymmetry exists in the impeller or diffuser blades, each passage of the damaged or corroded section can generate high-intensity vibrations within a specific harmonic. Additionally, the blockage of one or multiple diffuser passages can disrupt the uniform fluid flow patterns, resulting in elevated-amplitude vibrations within a particular harmonic.

Another mechanical factor to consider is the wear and tear of the casing or impeller wear rings, which can lead to an increase in the clearance between them. Using the pump's catalogue, pump schematic view and the location of casing and impeller wear rings is illustrated in Fig. 4. As it can be seen, the red area signifies the region where the casing and impeller wear rings come into contact. When the gap between these two rings falls within acceptable limits, they effectively function as a journal bearing. However, if either of the two rings becomes damaged or the clearance between them exceeds permissible thresholds, this can give rise to vibrations with significant amplitudes.

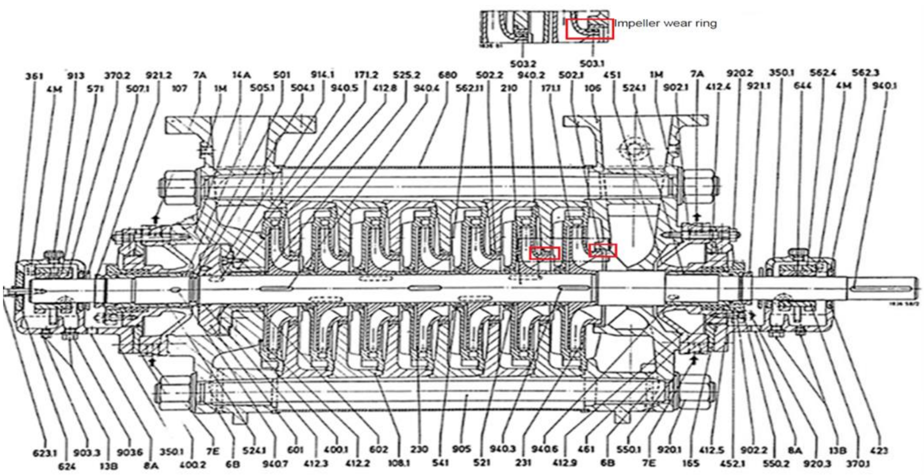


Figure 4. Pump schematic and the location of casing and impeller wear rings.

5. Conclusion

In this research, we performed vibration condition monitoring and fault diagnosis on a 7-stage centrifugal pump located at the Khatun Abad copper complex. To accomplish this, a vibrometer and accelerometer vibration probe were utilized for data collection, followed by an extensive analysis of the results. Our observations revealed that the vertical and horizontal vibration amplitudes in bearing number 3 were significantly elevated. Furthermore, the analysis of the vibration frequency spectrum in the bearings highlighted the prevalence of the tenth harmonic (approximately 491 Hz) with varying amplitudes across different directional components, particularly in the vertical direction. The presence of additional harmonics suggested the possible existence of mechanical issues within the pump.

Subsequently, an investigation into the source of the fault, taking into account both hydrodynamic and mechanical factors was performed. It was deduced that the primary mechanical factor contributing to the observed vibrations is damage or corrosion to the impeller or diffuser, resulting in asymmetry. Additionally, blockages in diffuser passages and wear ring clearance issues could also contribute to the amplified vibration amplitudes. To address the current problem and ensure the optimal performance of the pump, the following recommendations are proposed:

- It is imperative to assess the impact of variations in operational variables, such as flow rate and suction pressure, on the level of vibrations.
- A thorough examination of the impellers and diffusers is essential to identify any signs of corrosion or damage, particularly within the blade area or passages that may be obstructed. If impeller damage is detected, considerations should include replacement or modification and balancing. There is a higher likelihood of damage occurring in impeller or diffuser stages closer to bearing No. 3 due to the elevated vibrations.
- The casing and impeller wear rings should be inspected to assess for any damage and ensure that the gap falls within permissible limits.

Acknowledgements

"This research was made possible with the generous financial support from Sarcheshmeh copper complex and the valuable assistance of the R&D unit."

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