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Vibration-based detection of blower bearing defects using FFT and envelope analysis to improve machine reability

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Abstract
Rolling bearing failure in blower machines can disrupt plant operations, increase maintenance costs, and trigger unplanned shutdowns. This study aims to detect early-stage bearing damage in a blower unit at Plant Sabiz using vibration signal analysis. Vibration data were acquired using an SKF Microlog Analyzer CMDT 391 and evaluated using Fast Fourier Transform (FFT) and envelope analysis to identify defect-related frequency components. The results revealed an increase in velocity vibration up to 4.87 mm/s and envelope vibration up to 34.4 gE. The FFT spectrum showed dominant harmonics from 1xRPM to 3xRPM, indicating dynamic imbalance and potential damage to rotating components. Furthermore, envelope analysis identified bearing characteristic frequencies, particularly the Fundamental Train Frequency (FTF) and its harmonics, specifically pointing to cage degradation. This pattern was reinforced by the non-dominance of Ball Pass Frequency Outer Race (BPFO) and Ball Pass Frequency Inner Race (BPFI) frequencies, which ruled out damage to the outer and inner races. Visual inspection confirmed this interpretation, revealing cracks and breaks in the bearing cage. These findings confirm that combining FFT and envelope analysis is effective not only for early detection of bearing defects but also for identifying the specific type of damage based on frequency and harmonic patterns.

Keywords:
Rolling bearings, blowers, vibration, FFT, predictive maintenance

1 Introduction

Rolling bearings are critical components in rotating machinery, including industrial blowers, because their failure can cause operational disruptions, increased maintenance costs, and unplanned shutdowns [1] . Therefore, monitoring bearing conditions is an important part of a condition-based maintenance strategy.

Early diagnosis of bearing defects is generally performed through vibration signal analysis, as each type of mechanical damage produces a specific vibration pattern [2] . In the frequency domain, defects in bearings can be identified through the occurrence of characteristic frequencies such as Ball Pass Frequency Outer Race (BPFO), Ball Pass Frequency Inner Race (BPFI), Ball Spin Frequency (BSF), and Fundamental Train Frequency (FTF), which are related to damage to the outer race, inner race, rolling elements, and bearing cage, respectively [3] .

The FFT method is widely used to transform vibration signals from the time domain to the frequency domain so that the characteristic frequency patterns can be clearly observed [4] . However, in the initial state of damage, the defect signal is often masked by noise or other vibration components. Therefore, envelope analysis is used to extract high-frequency modulation signals that are directly related to impulses due to bearing defects, thereby increasing the sensitivity of early detection [5] . The combination of FFT and envelope analysis has been proven to improve the accuracy of identifying bearing defect types, especially in complex operating environments [6] .

As the concept of predictive maintenance evolves, data-driven approaches are becoming increasingly relevant within the industry 4.0 framework. Integrating vibration sensors with digital monitoring systems enables real-time data acquisition and analysis, supporting more informed maintenance decisions. In this context, FFT and envelope-based vibration analysis are key diagnostic methods that can be integrated into smart maintenance system. [7] .

Although numerous studies have explored bearing defect detection, most remain confined to laboratory environments or test rigs with controlled and relatively simple operating conditions. These conditions differ significantly from real industrial blower systems, which exhibit higher vibration complexity due to the interaction of various components and operating loads [8] .

Based on this, this study aims to apply a combination of FFT and envelope analysis methods in detecting bearing damage in industrial blowers operating under real conditions. This approach focuses not only on identifying the characteristic frequencies of defects, but also on interpreting vibration spectrum patterns to determine the type of damage more specifically. Thus, the research results are expected to provide a practical contribution in improving diagnostic accuracy and supporting the implementation of predictive maintenance in industrial systems [9] .

Fig. 1. Research object blower

2 Research methodology

In this study, bearing conditions were diagnosed by analyzing vibration signals in the frequency domain using FFT and envelope analysis. Vibration measurements were taken directly from the bearings of an industrial blower housing under normal operating conditions to gather actual data reflecting the system's dynamic response. The obtained vibration signals were then processed and analyzed to identify dominant frequency components, rotational harmonics, and bearing characteristic frequencies associated with specific types of damage. This research was conducted at a powdered soap production company, where damage to a blower bearing in August 2025 led to a 6-hour production shutdown.

a) Vibration due to bearing defects

The mechanism of vibration due to defects in bearings is the presence of an impulse when the element collides with a local defect. For a constant shaft rotation, the collision will occur periodically. For a single impulse force, the vibration response will be a damped free vibration [10] .

Some of the things that are often used to detect local defect damage are as follows:

Local defects in the inner race

$$BPFI = \frac{NB}{2} f_r x \left(1 + \frac{Bd}{Pd} x\ cos\alpha\right) \tag{1}$$

Local defects in the outer race

$$BPFO = \frac{NB}{2} f_r x \left(1 - \frac{Bd}{Pd} x\ cos\alpha\right) \tag{2}$$

Local defects in rolling elements

$$BSF = \frac{Pd}{2Bd} f_r x \left(1 - \left(\frac{Bd}{Pd} x\ cos\alpha\right)^2\right) \tag{3}$$

Local defects in cage

$$FTF = \frac{f_r}{2} x \left(1 - \frac{Bd}{Pd} x\ cos\alpha\right) \tag{4}$$

where,

Nb : Number of Balls.
Fr : Relative frequency between inner and outer paths, Hz.
Bd : Ball Diameter,mm.
Pd : Pitch diameter.
α : Contact Angle, degrees.

b) Blower specifications

The centrifugal blower used in this study moves air through a rotating impeller to generate the necessary pressure and flow rate. Air enters the impeller's center and is radially propelled towards the casing, increasing its pressure energy. Centrifugal blowers are commonly used in industrial systems, and their operational characteristics create continuous dynamic loads on bearings, making them ideal for vibration analysis and bearing damage detection. [11]. In Table 1 you can see the specifications of the blower used in this research object, the blower operates for 167 hours a week.

Table 1. Blower specifications

Specification	Technical Data
Manufacturer	Balestra SpA
Capacity	20,000 mc/ha 30˚
Static Pressure	400 mm. a 30˚
Total Pressure	4 mm. a 30˚
Velocity	1860/1'
Absorbed power	29.3 Kw at 30˚
Motor Pulley	300 x 3SPB
Fan Pulley	236 x 3SPB
Belts	N.3 SPB 3150
Support	ENBLOCK: OMB 60/N
Bearings	SKF 7211 BECBP
Motor Type	WUDF 2225 S
Kw	37
RPM	1470

c) Bearing specifications

The bearing used in this study is the SKF 7211 BECBP bearing. with industry standard sizes, which have ball-shaped rolling elements and are designed to support high rotation with low friction. The technical classification can be seen in Fig. 2.

Table 2 presents the main dimensional specifications of the bearing components used in this study. Each parameter includes its nominal size as well as its functional description, which plays an important role in ensuring the geometric suitability and overall system performance.

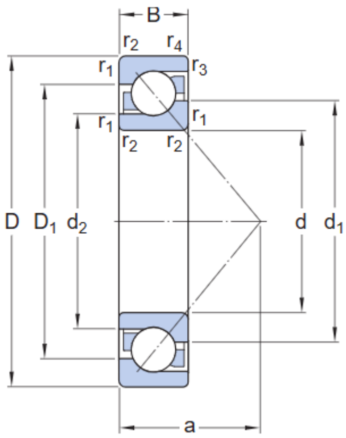


Fig. 2. Dimensions of SKF 7211 BECBP bearing

Table 2. Bearing dimensions

Symbol	Dimensions	Information
d	55 mm	Bore diameter
D	100 mm	Outside diameter
B	21 mm	Width
d_1	72.5 mm	Shoulder diameter of inner ring (large side face)
d_2	63.62 mm	Shoulder diameter of inner ring (small side face)
D_1	83.3 mm	Shoulder diameter of outer ring (large side face)
a	43 mm	Distance side face to pressure point
$r_{1,2}$	min. 1.5 mm	Chamfer dimension

Table 3 contains the technical specifications of the bearings which include load parameters and operating speed. This information is used as a basis for performance analysis and component selection in this study.

Table 3. Bearing specifications

Specification	Technical Data
Basic Dynamic Load Rating	49 kN
Basic Static Load Rating	40 kN
Reference Speed	8000 rpm
Limiting Speed	8000 r/min
SKF Performance Class	SKF Explorer

d) Level of bearing damage

The standard that is often used as an indicator of the level of vibration damage is ISO10816, where the parameter measured is vibration speed and compared with the RMS (Root Mean Square) value of speed based on the engine power classification.

Table 4. ISO 10816 bearing failure rates

<table>
<tr><th>RMS Vibration Velocity</th><th>Up to 15 kW</th><th>15 to 55 kW</th><th>>75 kW (Rigid)</th><th>>75 kW (Soft)</th></tr>
<tr><th>mm/s</th><th>Class I Machine</th><th>Class II Machine</th><th>Class III Machine</th><th>Class IV Machine</th></tr>
<tr><td>0.28</td><td rowspan="3">A</td><td rowspan="4">A</td><td rowspan="5">A</td><td rowspan="6">A</td></tr>
<tr><td>0.45</td></tr>
<tr><td>0.71</td></tr>
<tr><td>1.12</td><td rowspan="2">B</td></tr>
<tr><td>1.80</td><td rowspan="2">B</td></tr>
<tr><td>2.80</td><td rowspan="2">C</td><td rowspan="2">B</td></tr>
<tr><td>4.50</td><td rowspan="2">C</td><td rowspan="2">B</td></tr>
<tr><td>7.10</td><td rowspan="5">D</td><td rowspan="2">C</td></tr>
<tr><td>11.20</td><td rowspan="4">D</td><td rowspan="2">C</td></tr>
<tr><td>18.00</td><td rowspan="3">D</td></tr>
<tr><td>28.00</td><td rowspan="2">D</td></tr>
<tr><td>45.00</td></tr>
</table>

Letters A, B, C, D in Table 3. ISO 10816 Bearing Damage Level are evaluation zones, namely:

a. Zone A, namely vibrations in engines in good condition.
b. Zone B, namely vibrations in the machine with satisfactory conditions.
c. Zone C, which is vibration in the machine that is considered unsatisfactory for a long period of time.
d. Zone D, namely vibration values that are unacceptable because they can cause damage to the machine.

e) Research Tools

Some of the research tools used are as follows. First, a 49.61 HP (37 kW) WUDF 2225 S electric motor equipped with an inverter, hook spanner, torque wrench, and stroboscope. Then, an SKF Micrologic Analyzer (CMDT 391) was used to measure bearing vibration. In addition, a computer with SKF Analysis and Reporting Manager installed is also used . This tool is connected to a smartphone using a bluetooth network so that it can be used to collect vibration data.

Fig. 3. SKF microlog analyzer (CMDT 391)

In this study, the velocity (mm/s RMS) and acceleration (g) parameters were used. The velocity parameter is used as the main indicator for evaluating machine condition because it is able to represent the overall vibration energy and refers to the ISO 10816 standard. This parameter is effective for identifying various abnormal conditions that occur in the blower such as imbalance, misalignment, and increased vibration energy due to degradation of rotating components.

Meanwhile, acceleration is used in envelope analysis because it is more sensitive to high-frequency impulse signals generated by local defects in the bearing. Thus, velocity is used to evaluate the global condition of the machine, while acceleration is used for more specific early detection of bearing damage.

f) Vibration data collection position

Vibration measurements on bearings are typically conducted by installing accelerometers on the bearing housing in three main directions: horizontal, vertical, and axial. This approach is taken because each direction exhibits a distinct dynamic response to mechanical defects and operating conditions. This positioning ensures that recorded vibration signals accurately reflect frequency characteristics relevant to the bearing's condition, allowing for effective detection of each defect frequency within the vibration spectrum.[12] .

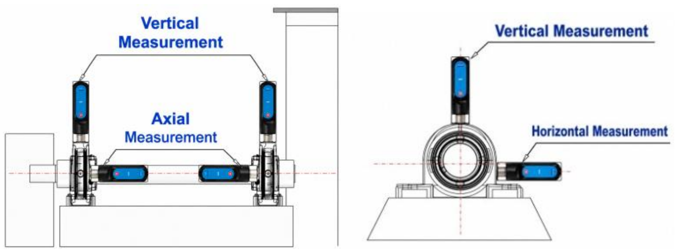


Fig. 4. Vibration measurement position

g) Data collection and data processing schematic

Sensor placement and measurement conditions

Vibration measurements were performed on the blower housing bearing using accelerometer sensors mounted in the horizontal and vertical directions. Data collection was carried out under normal operating conditions with an engine rotational speed of 1470 RPM=24.5 Hz . Sensor placement was carried out consistently at the same point to ensure representative signal acquisition of the bearing's dynamic response.

Signal acquisition and measurement parameters

The vibration signal was recorded in the time domain using a vibration analyzer with the following parameters:

- Sampling rate: 2.560 Hz
- Recording duration: 10 seconds per point
- Recorded parameters: velocity (mm/s RMS) and acceleration (g)

The sampling rate value was chosen to meet the Nyquist criterion so as to be able to capture frequencies up to 1.280 Hz, including rotational harmonics and frequency components relevant to bearing defects.

Signal pre-processing

The measurement signal is processed using windowing (Hanning) techniques to reduce spectral leakage, as well as averaging 2-4 times to increase spectrum stability and reduce the influence of noise from the industrial environment.

FFT setup and analysis

Signal transformation to the frequency domain is carried out using the FFT method with the following parameters:

- Frequency range: 0-500 Hz
- Number of lines: 1600
- Frequency resolution: ±0.31 Hz
- Windowing: Hanning
- Averaging: 2-4 times

This arrangement allows accurate identification of the main frequency components such as 1xRPM and its harmonics, and facilitates the separation of the bearing characteristic frequencies.

Filtering and envelope analysis

To detect local bearing defects, envelope analysis is carried out with the following stages:

- Application of band-pass filter in the range of 500-10.000 Hz to capture the resonance frequency
- Signal demodulation process (envelope detection)
- FFT transformation of the envelope output signal

This approach increases sensitivity to impulse signals due to bearing damage that are not visible in conventional FFT spectra.

Spectrum interpretation and damage diagnosis

Interpretation is done by identifying the spectrum peaks at the main frequencies such as 1xRPM, harmonics, as well as the bearing characteristic frequencies (FTF, BPFO, BPFI, BSF). Spectral patterns and amplitude increases are used to determine the damage indication and its severity.

Validation of results

The results of the vibration analysis-based diagnosis are validated through visual inspection of the physical condition of the bearing to ensure the correspondence between the characteristic frequency indications and the actual damage.

Based on this workflow, the bearing defect identification process is carried out in a structured manner starting from data collection, signal processing, to maintenance decision making, thus supporting the implementation of condition-based maintenance and increasing the reliability of the blower machine.

Fig. 5. Research method flow

3 Result and discussion

This study utilized vibration data from live industrial blower operating conditions, making it more representative of real-world scenarios and highly relevant for maintenance decision-making. The use of field data also enables the identification of more complex failure patterns than what can be observed using a test rig. However, industrial environments pose challenges such as noise, load variations, and speed fluctuations, all of which can affect signal quality and obscure early signs of failure. To address this, a combination of Fast Fourier Transform (FFT) and envelope analysis is employed. FFT identifies the dominant frequency, while envelope analysis extracts impulse signals indicative of bearing defects. This approach allows for accurate and consistent identification of characteristic frequency patterns and increasing vibration trends, aligning with visual inspection results.

FFT is commonly used to identify fundamental frequency components in vibration signals. The envelope spectrum, conversely, excels at highlighting impulses from bearing defects that might otherwise be masked by other spectral components. Combining these two methods significantly enhances the sensitivity of fault identification. [13] . Fault frequency components such as BPFO, BPFI, BSF, and FTF can appear on the FFT spectrum as repeated peaks, which are indicators of abnormal bearing conditions and can be distinguished from normal operating frequencies [14] .

Conventional FFT analysis can experience leakage or loss of frequency details when the machine vibration is not stationary or when the signal has high noise, so advanced methods such as envelope or wavelet are needed for more accurate diagnosis [15] .

In this study, the frequency values of FTF can be seen in Fig. 6 and 7. This figure shows a significant increase from day to day which results in fatal damage to the bearings and causes losses to the company.

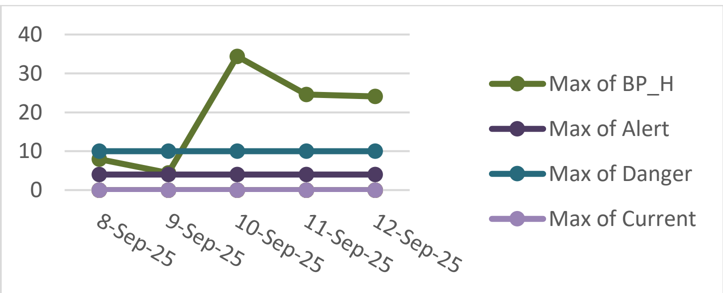


Fig. 6. Envelope graph

Fig. 6 shows an envelope graph with the trend of the maximum value of bearing vibration in the horizontal direction (BP_H) during the observation period of 8-12 September 2025, compared with the Alert and Danger threshold limits. At the start of the measurement, the BP_H value was at a relatively stable level and was still in a safe condition. However, on September 10, 2025, there was a significant increase in the BP_H value to near the Danger limit, which indicated an abnormal condition in the bearing system. In subsequent measurements, the vibration amplitude decreased, although it was still above the initial condition, indicating that bearing degradation was still ongoing.

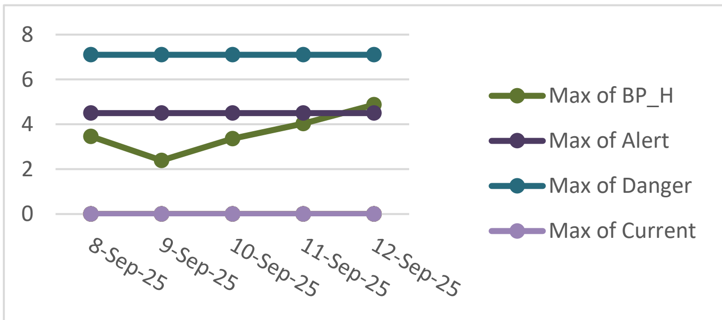


Fig. 7. Velocity graph

Fig. 7 shows a velocity graph with the development of the maximum vibration value in the horizontal direction (BP_H) during the observation period of September 8-12, 2025, compared to the Alert and Danger threshold limits. It can be seen that the BP_H value fluctuates and increases gradually until it reaches its highest value on September 12, 2025, approaching the Alert limit. This increasing pattern indicates a progressive degradation of the bearing condition, which is generally related to the instability of the bearing's internal elements such as the cage.

Table 5 shows the results of the envelope spectrum analysis, which aligns with the increasing trend of BP_H vibration values during the observation period. The highest envelope amplitude peak of 34.4 gE occurred on September 10, 2025, coinciding with a significant increase in the BP_H value on the trend graph, indicating the most critical bearing condition. On September 11 and 12, 2025, the envelope amplitude remained at a high level, at 24.6 gE and 24.1 gE, respectively, although the BP_H value began to decrease. This pattern indicates that vibration impulses due to mechanical degradation of the bearing are still ongoing. The emergence of dominant frequencies at multiples of RPM in the envelope spectrum strengthens the indication of bearing cage defects characterized by the FTF component and its harmonics, so that the envelope spectrum results are consistent with the threshold-based vibration trend analysis.

Table 5. Envelope data

Date	RPM	Frequency	Envelope
8-Sep-25	3x rpm and 6x rpm	65 Hz and 128 Hz	7.96 gE
9-Sep-25	5x rpm and 7x rpm	108 Hz and 150 Hz	4.41 gE
10-Sep-25	3x rpm and 7x rpm	65 Hz and 150 Hz	34.4 gE
11-Sep-25	8x rpm	170 Hz	24.6 gE
12-Sep-25	1x rpm and 3x rpm	65 Hz and 170 Hz	**3.1** gE

The envelope spectrum analysis in Fig. 8 shows the appearance of significant amplitude peaks at the bearing characteristic frequency and its multiples, which is consistent with the data in Table 5 Envelope and BP_H trends. The highest peak occurred on September 10, 2025 with an amplitude of 34.4 gE at frequencies of 3xRPM and 7xRPM (65 Hz and 150 Hz), indicating the presence of periodic impulses due to mechanical degradation.

The spectrum pattern, which is dominated by low to mid frequencies, points to an indication of bearing cage defects, characterized by discontinuous impulse excitation. Based on the evaluation against ISO 10816 criteria, the increase in envelope amplitude and vibration has entered the Alert zone to near Danger, thus indicating a decrease in blower reliability and the need for condition-based maintenance actions.

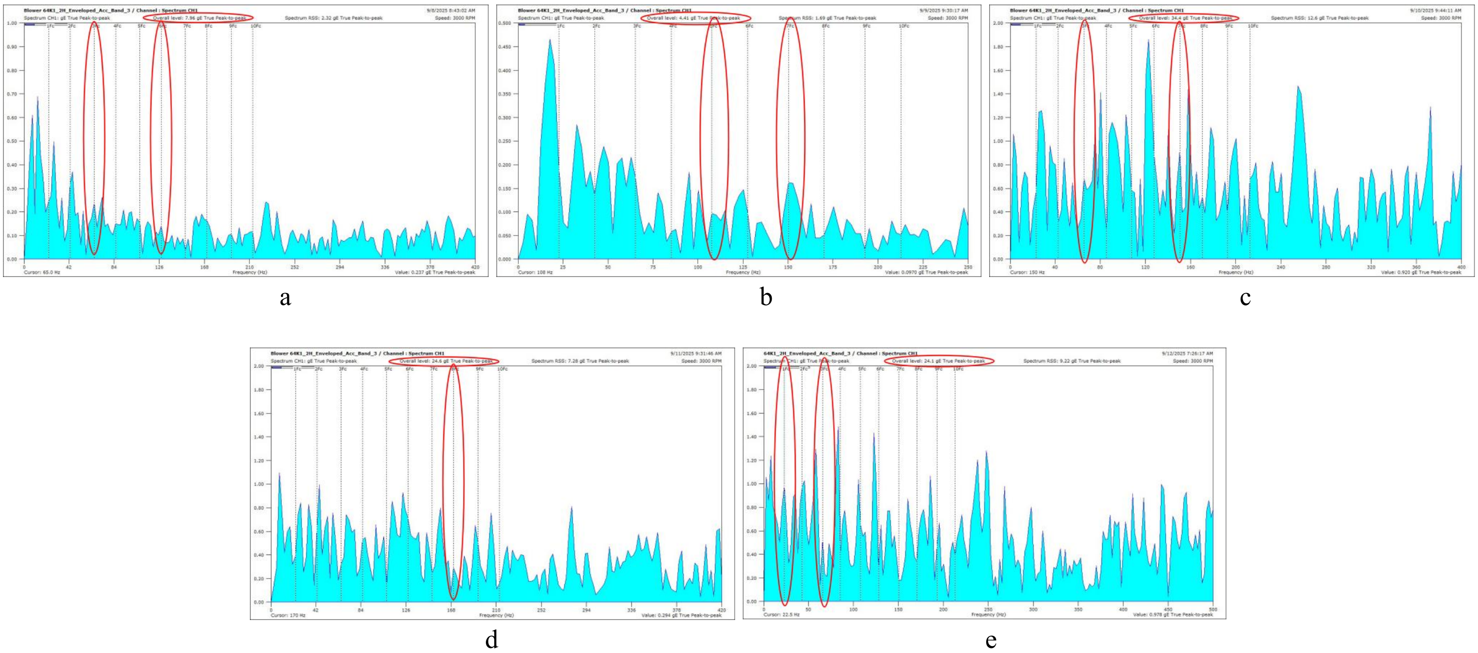


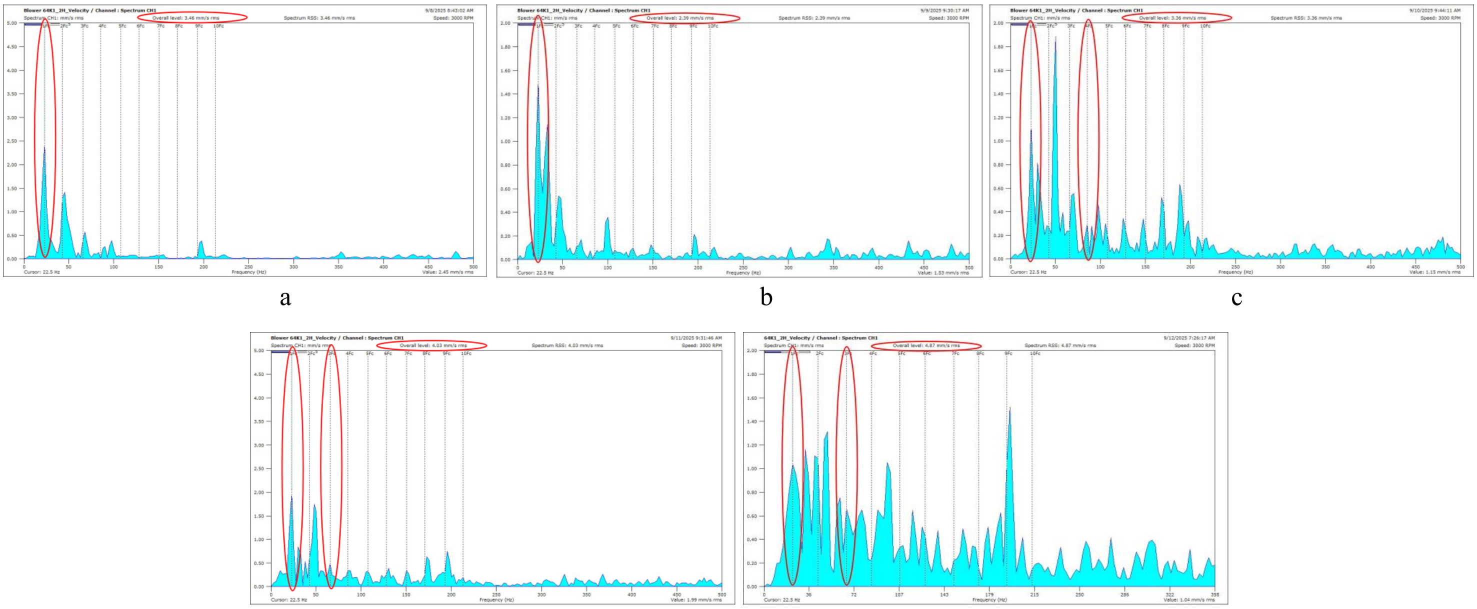
Fig. 8. Envelope spectrum

Table 6 illustrates a rising trend in vibration velocity values throughout the observation period. From September 8-9, 2025, vibration was primarily characterized by a 1x RPM component at 22.5 Hz, with a relatively low velocity, suggesting normal engine operation. On September 10, 2025, a 4xRPM component emerged at 85 Hz, accompanied by an increase in velocity to 3.36 mm/s, signaling an initial shift in vibration characteristics. Subsequently, on September 11 and 12, 2025, a 3xRPM component appeared at 65 Hz, with the velocity rising to 4.87 mm/s, indicating an escalation of vibration energy. This pattern of RPM harmonic appearance and increasing velocity points to degradation in rotating components and aligns with threshold-based vibration trend analysis.

Table 6. Velocity data

Date	RPM	Frequency	Velocity
8-Sep-25	1x rpm	22.5 Hz	3.46 mm/s
9-Sep-25	1x rpm	22.5 Hz	2.39 mm/s
10-Sep-25	1x rpm and 4x rpm	22.5 Hz and 85 Hz	3.36 mm/s
11-Sep-25	1x rpm and 3x rpm	22.5 Hz and 65 Hz	4.03 mm/s
12-Sep-25	1x rpm and 3x rpm	22.5 Hz and 65 Hz	4.87 mm/s

Fig. 9 displays the FFT velocity spectrum on the blower bearing, revealing a dominant amplitude peak at the fundamental rotation frequency (1xRPM) and its harmonics. The emergence and intensification of these harmonic components signal dynamic excitation tied to the rotating machine's operational conditions, such as imbalance and shaft misalignment. Furthermore, the presence of additional peaks with increased amplitude at specific frequencies points to abnormal mechanical interactions within the bearing, potentially stemming from degradation of the cage and rolling elements. Consistent spectral patterns across multiple measurement points indicate a deteriorating bearing condition. Thus, FFT velocity analysis can serve as an early indicator for reliability assessment and the planning of preventive maintenance actions, aligning with the vibration criteria outlined in the ISO 10816 standard.



a b c

d e

Fig. 9. Velocity spectrum

An increase in amplitude at multiples of the rotational frequency in the velocity spectrum usually indicates developing damage to the bearing due to increasingly strong mechanical resonance [16] .

The frequency spectrum results obtained show a typical harmonic pattern of bearing damage. A similar pattern was also found in a condition monitoring study on industrial shaft bearing systems, where the dominant frequency was used as the primary predictor of bearing wear levels. These findings are in line with the results of this study which showed an increase in amplitude in the BPFI frequency band [17] .

Vibration-based condition monitoring has been shown to reduce unplanned downtime and increase overall machine reliability, as damage can be identified before total failure [18] .

Based on FFT and envelope spectrum analysis, harmonic and amplitude patterns were obtained that increased with operating time, which indicated a spalling process in the bearing cage. This finding is in accordance with the defect characteristics, where the combination of time- frequency domains provides the most stable diagnosis results for high-speed rotation systems such as industrial blowers [19] .

Fig. 10. Broken cage

Fig. 10 shows the actual condition of the rolling bearing after disassembly, where severe damage is visible to the cage section, marked by a broken cage structure and the release of the rolling elements (balls). This damage indicates progressive mechanical degradation due to repeated dynamic loads and high vibration excitation during blower operation. Cage failure causes the bearing to be unable to maintain the position and clearance between the rolling elements, thus triggering abnormal contact, increased friction, and vibration spikes. This physical condition aligns with the previous FFT and envelope spectrum analysis results, which showed the appearance of FTF frequencies and their harmonics, which are characteristic of cage damage in rolling bearings. This visual inspection validates the vibration signal-based diagnosis results and confirms the effectiveness of the FFT and envelope analysis method in detecting bearing defects early before total failure occurs.

4 Conclusion

This research shows that vibration signal analysis-using FFT and envelope methods effectively detects bearing damage in industrial blowers under real operating conditions. FFT provides an overview of dominant system frequencies, while envelope analysis improves sensitivity to impulsive signals associated with localized defects. The spectrum interpretation indicates that damage is more strongly suggested by the appearance of frequency components related to the FTF, along with their modulations or harmonics, which point to the degradation of the bearing cage. Conversely, the appearance of rotational harmonics (1xRPM and its multiples) more accurately reflects general dynamic response of the system and requires careful interpretation to avoid direct association with bearing-specific defects. These signal-based diagnostic results align with visual inspection findings of cage damage, thereby reinforcing the reliability of this approach. Overall, this study demonstrates that FFT and envelope-based vibration analysis is a relevant diagnostic method for bearing condition monitoring in industrial environments.

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