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FAULT DIAGNOSIS OF HIGH-SPEED ROTATING MACHINES USING MATLAB

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Abstract

Industrial high-speed rotating machines entail constant and consistent monitoring to prevent downtime, affecting quantity and quality. Complex machines need advanced intelligent fault diagnosis showing minimal errors. This work offers a MATLAB-based fault diagnosis for sugar industry machines. The vibration behavior of physical industrial machines is obtained, and the signals are provided to a MATLAB program to identify the fault. The information helps to suggest remedies to include in the maintenance schedule. The ease and comprehensible nature of the method reduce time and enhance the reliability of condition monitoring for industrial machines.

Keywords: Fault Diagnosis, Condition Monitoring, MATLAB

1. INTRODUCTION

Industrial machine maintenance includes corrective, i.e., run-to-failure maintenance and predictive maintenance. The selection and actual implementation of the type of maintenance in the plant usually depends on policy and practice. The run-to-failure maintenance may be economical up to the first failure. Because when it is applied, the users have more risk and, therefore, no longer acceptable for large complex machines, where the losses due to an unexpected production stoppage are substantial. Predictive maintenance involves scheduled maintenance and condition-based maintenance. Machine manufacturers often recommend scheduled maintenance that may result in high costs because of an unnecessarily short time between overhauls and performed maintenance, whether an overhaul is needed or not. Condition monitoring is a crucial tool for the predictive maintenance of machines by monitoring significant operational parameters such as vibration, noise, and temperature effectively to diagnose imminent faults and maintain the machine's health. The key reason to follow machine condition monitoring and fault diagnosis is to accumulate quantitative and accurate info on the machine's current state, ensuring its realistic performance. Condition monitoring helps schedule or execute appropriate actions to avoid catastrophic failure before the actual loss.

Many researchers reported diverse methods for fault diagnosis in the condition monitoring of industrial machinery. Shin et al. [1] summarized the working of in-process plants in which many failures occur due to the operator's lack of knowledge. A geometrical property of types of equipment provides necessary information regarding the health of machines. According to the authors, condition monitoring is essential for production plants. Joshi et al. [2] presented the process of implementing vibration monitoring and analysis to solve the problems in the sugar industry and claimed a powerful tool for fault diagnosis of rotating machinery. Frequency analysis detects the exact type of fault, which is eased well in advance before the catastrophic failure of the machine. With advancements in vibration monitoring and analysis instrumentation, maintenance personnel saves much more in terms of workforce, money, and downtime.

Mokhtar et al. [3] recommended condition monitoring of rolling bearings, the most fragile rotating machine components, with many statistical approaches for precise and accurate fault diagnosis to avoid unforeseen stoppages and expensive production. Khadersab et al. [4] discussed the area of applications of rotary machines in day-to-day life. For rotary machines, the faults induced due to bearing failure play a vital role in machinery failure subjected to fatigue and catastrophe. Under the various maintenance techniques, vibration analysis has been an all-embracing technique to assess the rotating machines' health accurately. The inverse Fast Fourier Transformation technique has been popular for analyzing bearing failures. Tandon et al. [5] developed a mathematical model to study the effects of distributed faults on the vibration response of rolling element bearings under radial force conditions. The model considered the faults in the outer race, inner race, and off-size moving element. The model forecasts the amplitudes of the spectral components due to outer race waviness much higher than those due to inner race waviness. Dolenc et al. [6] investigated the bearing vibrations of distributed faults and noticed the imminent defects using vibration analysis.

Desavale et al. [7] described the experimental data-based model to determine the vibration characteristics and frequency of the antifriction bearing. The model developed using Dimension analysis predicted vibration amplitude satisfactorily and presented industrial case studies for validation. Shah et al. [8] analyzed the vibration characteristics of rolling element bearings using numerical analysis and diagnosed local and distributed faults. As a result, simulation and numerical analysis effectively investigated the frequency and vibration amplitude characteristics. Patel et al. [9] conducted an experimental study on vibration behaviors of deep groove ball bearings under dynamic radial load for local faults. Also, Tiwari and Gupta [10] studied the dynamic response of an unbalanced rotor supported on a ball bearing for nonlinear dynamic analysis. In condition monitoring, the studies claimed considerable potential for fault diagnosis methods for industrial rotating machinery. Kumbhar et al. [11-13] demonstrated the development of mathematical models considering geometric, thermal, and operational structure parameters for bearings using dimension theory. The identification of exact bearing failure and effective prediction is achieved using intelligent techniques aligned with dimension theory, showing improved performance of the diagnosis methods. Salunkhe et al. [14-15] utilized the matrix technique to forecast the vibrations associated with dependent parameters. Formulated model is solved numerically by a support vector machine (SVM). The influences of various parameters like rotor speed and bearing faults are well predicted, showing the power of SVM for bearing fault diagnosis.

To inculcate artificial intelligence for condition monitoring in various industrial fields, many software has been adopted and utilized in the fault diagnosis of machines. MATLAB is a high-end matrix/ array language software with controlled flow statements, data structures, and object-oriented programming features. It avoids personal errors, achieves considerable accuracy, and maintains consistency. Howard [16] has outlined the use of MATLAB software for vibration signal processing and concluded that its interactive nature, the multiplatform capability of MATLAB, and the ability to link in existing code enhance its usefulness for critical problems. Moreover, the industrial application of MATLAB easily handles more complex vibration condition monitoring problems. Sarje et al. [17] devised a CBM policy for an online constantly monitored deteriorating system with an unexpected change of mode and suggested an online continuous monitoring maintenance decision rule.

Gopinath [18] et al. analyzed the signal behavior between the time and frequency domain when the shaft rotates at a critical speed and also showed the signal's filter specifications. Two signal domains through FFT were analyzed and compared using the presented tool and showed the inverse behavior between these domains, ultimately avoiding the failure of shafts and enhancing the life of the machines, such as turbines and gearboxes. Thakur et al. [19] reviewed Electro-mechanical components and discussed that these often require automated online test systems to monitor the characteristics of all their products and parts precisely. Condition monitoring of manufacturing equipment often relies on the analysis of the vibration of the machine, where the occurrence of an error can show the difference in the vibration signal produced by it. Huang et al. [20] presented MATLAB code for the Multiple Time-Frequency Curve Extraction algorithms. The MTFCE code is used for automatic bearing fault diagnosis under time-varying speed conditions without measuring the speed. The results claimed that the code and methodology could effectively diagnose the bearing faults under time-varying speed conditions.

Fault diagnosis of the industrial rotating machinery and remedial action includes the judgment that varies from person to person and is usually subjected to errors. To overcome these limits, a simple and user-friendly MATLAB-based program can be designed for fault diagnosis and applied to suggest corrective action for critical types of equipment in sugar industries. Sophisticated signal processing techniques may be developed quickly with flexibility and interactive nature in MATLAB. The present work involves the development of a MATLAB program and its implementation for fault detection in industrial rotating machinery. An FFT output signal is supplied as input to the program, and the output is in the form of machine problem statements which helps to suggest remedies. It forms the novelty of the work over reported studies. The study contributed to the field as a method of revealing machinery health by automatically processing vibrations signals using MATLAB. Further, section 2 presents condition monitoring, and section 3 describes the MATLAB program. Section 4 describes the experimentation, and 5 discusses the results and discussion, whereas section 6 proposes the conclusions.

2. CONDITION MONITORING FOR SUGAR INDUSTRY

In India, sugar factories run for a particular season, generally 4-5 months a year. The breakdown of any single critical or semi-critical machine can cause significant downtime and increase repair and maintenance costs. For example, the failure of a single bearing of fiberizer prices around 3 lacks in rupees and takes at least 6 hours to replace. Preventing such a colossal loss and keeping machines in operation without failures call for predictive maintenance technique that uses vibration monitoring and analysis that can detect both the nature and severity of the defect and forecast the machine's useful life. To implement condition-based maintenance and perform condition monitoring in the sugar industry, it is desirable to distribute the individual sections. A typical sugar industry consists of four sections: Mill section, Boiler section, Juice section, and Powerhouse. Table 1 represents the power and speed rating of significant types of equipment in various sections of the sugar industry, and Table 2 classifies their machines based on power rating.

Table 1. Power and speed ratings of major equipments

Parameters	Leveler	Fiberizer	I.D. Fan	F. D. Fan
Power (kW)	300-600	750-1000	300	150
Speed (rpm)	600	700	700	1440

Table 2. Classification of Machines and Vibration Severity as per ISO 2372 (10816) [21]

RMS velocity for vibration severity (mm/s) (RMS)	Vibration velocity for a separate class of machine			
	Class I	Class II	Class III	Class IV
0.28	A	A	A	A
0.45	A	A	A	A
0.71	B	A	A	A
1.12	B	B	A	A
1.8	B	B	A	A
2.8	C	B	B	A
4.5	C	C	B	B
7.1	D	C	C	B
11.2	D	D	C	C
18	D	D	D	C
28	D	D	D	D
45	D	D	D	D
71	D	D	D	D

Class I includes small machines with normal operating conditions, i.e., electrical motors up to 15 KW. Class II consists of Medium-sized machines, i.e., 15- 75 KW electrical motors and 300 KW engines on special foundations. The heavy-duty prime mover or a machine placed on a stiff foundation belongs to class III. Similarly, large prime movers placed on relatively soft, lightweight structures are clustered in Class IV. Table 2 specifies the acceptable vibration range for the above classes. Vibration severity is divided into four ranges, the letters A, B, C, and D representing machine vibration quality grades, ranging from A: Good (smoothest) to D: unacceptable (roughest).

3. DEVELOPMENT OF MATLAB ALGORITHM

For rolling element bearings, the ball pass frequencies are calculated using standard equations for the inner race, outer race, and rollers. The calculated values for particular bearings are used for designing the algorithm. To develop the program, it is considered that the vibration amplitudes associated with the ball passage frequency reduce for larger preloads, and an increase in the number of balls reduces the vibration amplitude [22].

The signals corresponding to Horizontal, Vertical, and Axial directions are considered.

3.1. Horizontal Direction Vibration Analysis

1. Input the machine details: machine name, rpm, power, and bearing number.
2. Select the drive side: non-drive or drive
3. Select Direction: 1. Horizontal 2. Vertical 3. Axial = Horizontal
4. Input vibration signal and compute N=RPM/60
5. Check whether the vibrations are within acceptable limits or not by comparing the vibration spectrum below N with some threshold value (e.g., 5).
6. Check the dominant vibration amplitude, i.e., the Highest peak (Hamph), and perform the analysis.
7. Analysis:

If [f(Hamph)< N-1]
then display, the machine is 'Ok.'
elseif [N-0.5<=f(Hamph)< N+0.5]
then display 'Balancing Problem';
elseif [(1.5*N-1.5)) <=f(Hamph) < (1.5*N+1.5)]
then display 'Bearing Cage Problem' ;
elseif[(2*N-1.5)) <= f(Hamph) < (2*N+1.5)]
then display 'Bearing looseness or misalignment';
elseif [((37.8*N)-1.5)) < f(Hamph) < ((37.8*N)+1.5)))
then display 'Bearing problem: Rolling element defect';
***(441/N=37.8)
elseif((4.05*N)-1.5)) < f(Hamph) < ((4.05*N)+1.5)))
then display 'Looseness/parallel misalignment problem - Outer race defect';
***(47.25/N=4.05)
elseif((4.56*N)-1.5)) < f(Hamph) < ((4.56*N)+1.5)))
then display 'Looseness/parallel misalignment problem - Inner race defect.'
***(53.18/N=4.56)

8. Print report of comparison analysis

3.2. Vertical Direction Vibration Analysis

Repeat the above algorithm for horizontal analysis by replacing the frequency of the highest peak amplitude of horizontal signal 'f(Hamph)' with the highest peak amplitude of Vertical signal 'f(Hampv)

3.3. Axial Direction Vibration Analysis

The stepwise program procedure is as follows:

1. Input the machine details: machine name, rpm, power, and bearing number.
2. Select the drive side: non-drive or drive
3. Select Direction: 1. Horizontal 2. Vertical 3. Axial = Axial

4. Input vibration signal and compute N=RPM/60
5. Check whether the vibrations are within acceptable limits or not by comparing the vibration spectrum below N with some threshold value (e.g., 5).
6. Check the dominant vibration amplitude, i.e., the Highest peak(Hampax), and perform the analysis.
7. Analysis:
8. If [f(Hamph)< N-0.5]

then display, the machine is 'Ok.'
elseif [N-1.5<=f(Hamph)<N+1.5]
then display 'Angular Misalignment Problem';
else [f(Hamph) >=(N+1.5)]
then display 'Clearance Problem';

9. Print report of comparison analysis

4. EXPERIMENTATION - INDUSTRIAL CASE STUDIES

A preliminary survey is conducted to gain the functions, criticality, technical specifications, and cost of machines used in the sugar industries. Approximately 80% of sugar industries across Maharashtra are visited in this survey. After analyzing the collected data, Fig. 1 shows the average percentage of lost hours due to different regions in the Indian sugar industry during the crushing season, which is 17.07 (region-wise lost hrs), and the percentage of stoppages due to mechanical faults during the crushing season 2012-13 in Maharashtra lies in the range of 2.1 to 6.5. (Fig. 2).

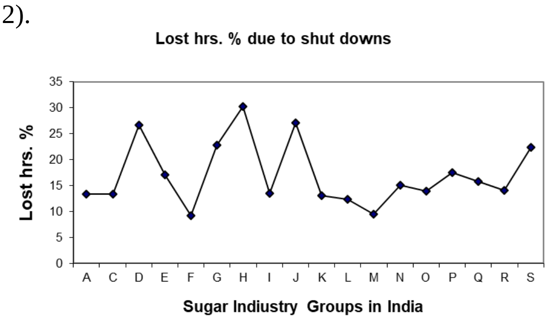

Fig. 1. Percentage of stoppages due to mechanical faults in India

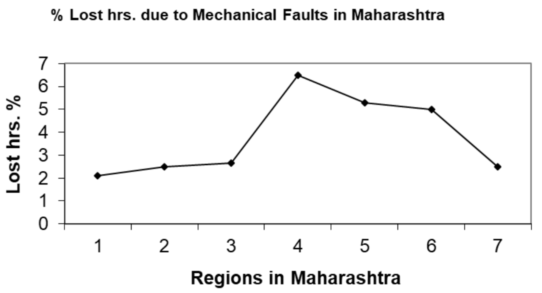

Fig. 2. Percentage of stoppages due to mechanical faults in Maharashtra

The preliminary survey of the vibration problems in sugar factories revealed that the Leveler, Fiberizer, ID fan, and F. D. fan are vital machines. Failures of these machines are reported when subjected to severe operating conditions, leading to unbalance, misalignment, wear and tear, and fluctuating conditions. Significant downtime of the sugar factory resulted due to the failure of these machines. Break down of one of these machines results in costly repairs /replacements and almost complete closure of the plant operation. No stand-by facilities are available for them because of the higher cost. Hence, these four machines are treated and confirmed as critical machines. Failure of pumps, centrifuges, and blowers does not interrupt plant operation because stand-by facilities are available for these machines. The material flow is often diverted to other similar machines, and repair or replacement is carried out. Therefore, it is clear that Leveller, fiberizer, ID, and FD fans are critical machines, and a preventive maintenance program should cover these machines.

Condition monitoring of various rotating machinery is carried out to identify many faults, such as surface faults, misalignment, unbalance, clearance, and looseness, observed in sugar industries. Single number indicators of damage (X(t)), such as displacement, velocity, and acceleration, are used to set up the program. Time and frequency domain parameters are used to obtain the results. The adopted procedure involved the following steps -

1) Measurement of overall vibration levels on the bearings of the machine.
2) Frequency and phase analysis of the vibration in the abnormal situation
3) Diagnosis of the fault from the analysis; and
4) Rectification of the fault

For example, the Vishwasrao Naik Sahkari Sakhar Karkhana Ltd., Yashwantnagar, Chikhali, Maharashtra, India, consists of a motor-driven fiberizer, and its motor rotates at 700 rpm and has a self-aligned, oil-lubricated double row spherical roller bearing with taper sleeve. During condition monitoring, excessive vibrations of fiberizer are experienced before the crushing season's start and reported during a trial run. Vibration measurement was carried out at the driving and non-driving end bearings of the fiberizer (Table 3). A greater vibration level was observed at the driving end with a velocity of 7.56 mm/sec. It is also seen that vibration levels at both bearings were fluctuating, and these levels are not acceptable.

Fig. 3 shows the layout of Fiberizer and whose responses are collected from the sugar industry.

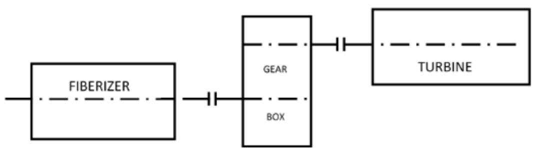

Fig. 3. Layout of fiberizer

In the analysis and diagnosis, vibration analysis was carried out with an FFT analyzer to pinpoint the cause of vibration. Fig. 4 shows the frequency spectrum taken on the driving end bearing of the fiberizer with pick-up mounted in the horizontal direction. The frequency spectrum revealed the predominant peak at 2 x rpm of the fiberizer. Little marked peaks are also at 1 x rpm. The vibrations at 2 x rpm invariably cautioned us to check alignment and looseness.

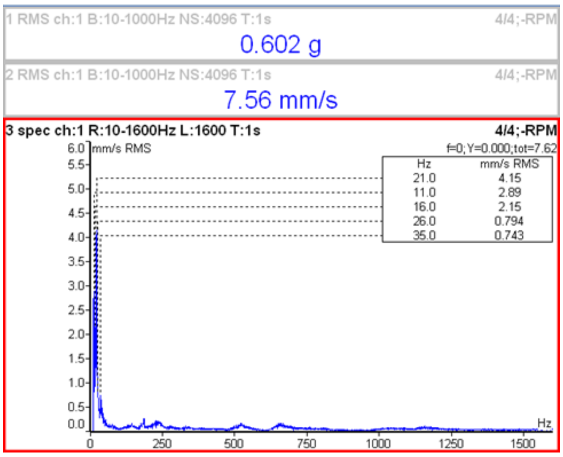

Fig. 4. Frequency spectrum of Drive End bearing of fiberizer (no.2) in the horizontal direction (before rectification)

The alignment of the coupling assembly was checked and found correct and within permissible limits. All the foundation and pedestal bolts were checked and found in tight condition. After checking the alignment and bolts, the fiberizer was restarted to observe the vibrational performance under no-load conditions. The vibration level was similar, and the phase observed using the stroboscope was erratic. After opening the driving end bearing pedestal assembly, the loosely fitted bearing inner race was observed on the bearing sleeve, and the sleeve itself was damaged. Moreover, 350 microns bearing clearance was found, which is more than permissible.

The vibration response of a fiberizer obtained using data acquisition systems and processed using FFT is supplied to the developed MATLAB program, and results are observed. It is seen that the MATLAB software shows the presence of clearance in the bearing. Fig. 5 represents the fault for Fiberizer, and the peak is observed at 2 x rpm frequency.

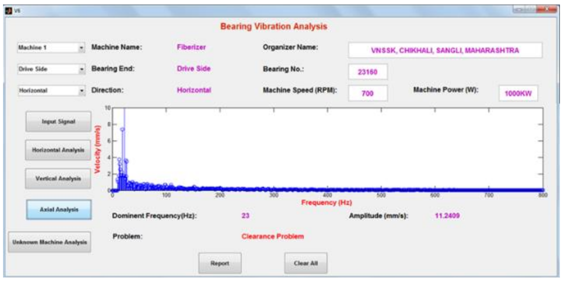

Fig. 5. MATLAB program detected Fiberizer's bearing clearance fault

The bearing sleeve was replaced in rectification, and the clearance was reduced by tightening the sleeve correctly. A new sleeve was placed and tightened to achieve recommended 250 microns clearance. After this rectification, the fiberizer was restarted and found to be in usable condition. The overall vibration velocity level at both bearings is reduced. The maximum velocity recorded after rectification was 1.23 mm/sec, which was in a functional zone of the vibration criterion. The frequency spectrum obtained after rectification (Fig. 6) shows a substantial peak reduction at 2 x rpm. Early detection of the fault and its subsequent rectification prevented the production loss.

For all rotating machinery in the various sugar industries, vibrations responses of critical machines are recorded using the multi-channel FFT analyzer. It is observed that the faults induced bearing faults contributed significantly to machines' failure.

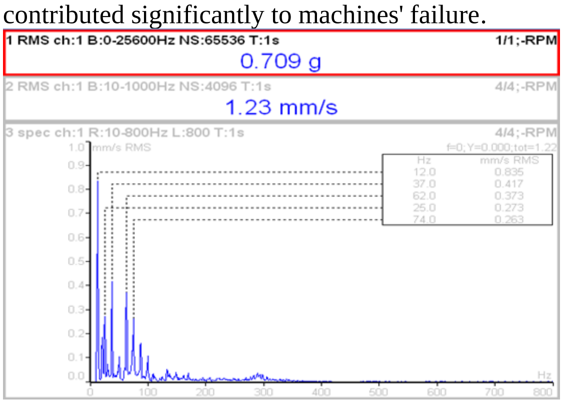

Fig. 6. Frequency spectrum of Drive End bearing of fiberizer in horizontal direction after rectification of the fault.

Table 3. Vibration readings of fiberizer before rectification

Measurement locations and directions		Vibration Levels				
		Velocity mm/sec (RMS)	Acceleration g(RMS)	At frequency 1xRPM mm/sec(RMS)	At frequency 2XRPM mm/sec(RMS)	At higher frequency mm/sec(RMS)
Drive End	Horizontal	7.56	0.602	2.89	4.15	0.74
	Vertical	1.03	1.67	0.28	0.74	-
	Axial	1.03	0.99	0.31	0.5	-
Non-Drive End	Horizontal	1.4	2.5	0.5	0.68	-
	Vertical	1.28	2.0	0.14	0.6	0.8
	Axial	0.81	1.5	0.37	0.32	-

The bearings were continuously monitored for their conditions. The obtained responses are supplied to the developed MATLAB program that detects the exact type of fault. The information revealed is used to suggest remedies, and the faults are rectified well before a catastrophic machine failure. The significant results of these case studies are discussed in the following section.

5. RESULTS AND DISCUSSION

The developed MATLAB algorithm is applied for fault detection that helps to recommend remedial action for significant equipment in various sections of the sugar industry. The vibrations signals of the industrial machines in frequency spectrums are obtained using the data acquisition system. The FFT analyzer output signals (in Excel format) are supplied as input to the developed MATLAB-based program. This signal is analyzed and processed, and the output is displayed. Fig. 4 to 8 represents the photographs of the program application for various faults identified for powerful machines.

5.1. Machine 1: Fiberizer

The vibration response of a fiberizer is obtained using data acquisition systems and processed using FFT. The data is supplied to the developed MATLAB program, and results are observed. It is seen that the MATLAB software shows the presence of an inner race fault in the bearing. Fig. 7 represents the inner race-bearing defect for Fiberizer. The peak is observed at Nxn frequency.

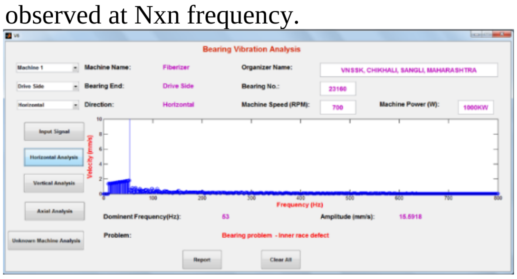

Fig. 7. Fiberizer's bearing inner race defect

The diagnosis revealed the fault; hence, the maintenance team performed corrective action based on the strategic schedule. Fig. 8 describes the machine vibrations of the Fiberizer within the acceptable limit.

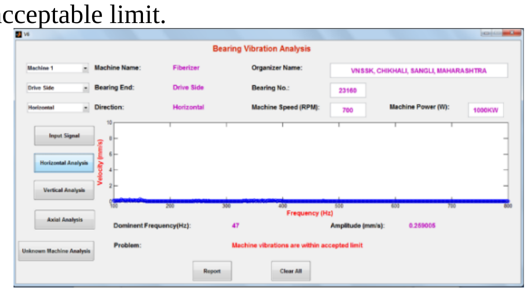

Fig. 8. Fiberizer's acceptable bearing condition

5.2. Machine 2: Leveler

The vibration response of a leveler is obtained using data acquisition systems and processed using FFT. The results are observed after data processing based on the developed MATLAB program. The occurrence of clearance in the bearing is exposed in the results. Fig. 9 represents a clearance problem for the leveler. The peak is observed at 2 x N frequency. As per the strategic schedule, the maintenance team performed the corrective action.

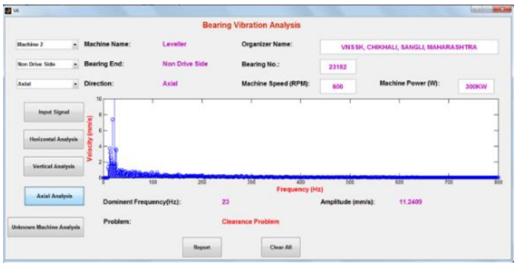

Fig. 9. Leveler's Bearing Clearance Problem

5.3. Machine 3: ID. Fan

The data acquisition systems and FFT analyzer is utilized to collect and process the vibration response of ID fan in the sugar industry. After data processing in the developed MATLAB program, an outer race defect is discovered in the bearing. Fig. 10 represents the bearing problem, outer race defect for I. D. Fan. The peak is observed at Nxn frequency. As per the strategic schedule, the maintenance team performed the corrective action.

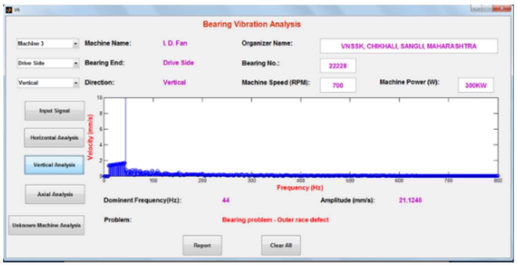

Fig. 10. ID Fan's Bearing outer race defect

5.4. Machine 4: FD Fan

The vibration response of ID fans in the sugar industry is obtained using data acquisition systems and the FFT analyzer. The developed MATLAB program is applied over the signal, and the bearing cage problem is disclosed in the bearing. Fig. 11 describes the bearing cage problem for the FD Fan. The peak is observed at N x 1.5 frequency. As per the strategic schedule, the maintenance team performed the corrective action.

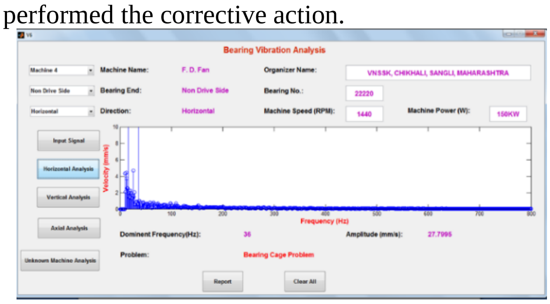

Fig. 11. F. D. Fan's Bearing cage defect

In the program, the bearing defect is correlated with ball pass frequencies for each bearing. The defects such as misalignment, cage problems, unbalancing, and bearing looseness are associated with running frequency, i.e., the rotating speed of the particular machine. After fault detection, the program provides information about faults, which can help to recommend possible remedies for overcoming the defect.

6. CONCLUSION

Critical and complex industrial machines demand software-based condition monitoring to avoid human errors. The present work shows a MATLAB-based fault diagnosis to identify faults in high-speed rotating machines in the sugar industries. The vibrations responses of various machines are obtained using an FFT analyzer, and the MATLAB algorithm is applied for fault detection and remedial action. The following conclusions are drawn:

1. The survey reveals that about 75% of breakdowns in sugar industries are due to mechanical faults in critical machines, namely levelers, fiberizer/shredders, ID Fans, FD Fans, SA fans, and turbines. The use of preventive maintenance techniques is the best solution to reduce downtimes.
2. The measured vibration amplitude and fault frequencies closely match the calculated theoretical frequency.
3. The MATLAB program output display shows a particular fault.
4. The program quickly indicates minor and major faults in critical machines from the sugar industry
5. The MATLAB-based software suggests suitable remedial actions for a particular fault in a separate report.
6. Any low-skilled and non-technical person can easily use the developed program.
7. Overall, the simplicity and effectiveness of the presented MATLAB-based condition monitoring perform fault diagnosis at early stages and reduce the catastrophic effect, which ultimately reduces maintenance costs and machinery downtime.

The present work can be extended by developing IoT-based in-situ online condition monitoring of industrial machines in which a continuous supply of vibration responses for processing and display results and remedies.

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