Military Technical College
Kobry El-Kobbah,
Cairo, Egypt.

18th International Conference
on Applied Mechanics and
Mechanical Engineering.

MACHINE HEALTH MONITORING USING VIBRATION ANALYSIS

E. A. Nabby[1], M. H. Belal[2] and F. R. Gomaa[3]

ABSTRACT

Vibration analysis is an effective tool to identify and predict failure using Signal Processing based on condition monitoring. Accordingly, machine faults can be detected and diagnosed using different post processing of vibration signature. The present study is to prove that Machine Health and availability achievement becoming easier by using different vibration analysis techniques. Three different types of nonstationary signals are addressed in this paper to evaluate the technical conditions of Paper Machine Forming Roll. Forming Roll consists of frequency drive motor, gearbox and a symmetric rotor supported on two similar bearings. The present study is focusing on Forming Roll Bearings Condition Monitoring. A cost wise comparison of maintenance strategies is made to confirm that Condition based Maintenance is the most cost-effective strategy. In the past portable data-collectors were used to measure vibration levels, but Condition based Monitoring had taken place to avoid any sudden fault developing before next time schedule. Applying different vibration analysis techniques such as Spectrum, Waveform and Impact Demodulation will support fault detection, diagnosis and decision-making. The present study proved that Impact demodulation is recommended to specify faulty bearing source location and severity, while time waveform or spectrum analysis techniques can detect fault progress but couldn’t distinguish severity due to bearings similarity. Based on Impact Demodulation technique decision is made to exchange only the higher severity faulty bearing and postponed the other one for next planned shutdown. Consequently, the machine availability and health can be achieved by reducing vibration impact around 100 % through continuous condition monitoring.

KEY WORDS

Bearings Monitoring, Forming Roll, Machine Health, Vibration Analysis, Impact Demodulation, Envelope Technique, Paper Machine, Signal Processing.

---

[1] Graduate student, Dept. of Production Engineering and Mechanical Design, Faculty of Engineering, Menoufia University, Shebin EL-Kom, Egypt. Email: Eman.abdelnabby25@gmail.com

[2] Dr., Dept. Production Engineering and Mechanical Design, Faculty of Engineering, Menoufia University, Shebin EL-Kom, Egypt. Email: Heshambelal@gmail.com

[3] Professor, Dr., Dept. of Production Engineering and Mechanical Design, Faculty of Engineering, Menoufia University, Shebin EL-Kom, Egypt. Email: Fawkiagomaa@yahoo.com

NOMONCLATURE

1XM	Motor RPM
1XN	Roll RPM
A(n)	Amplitude of the nth digitized point in the time domain
BSF	Ball Spin Frequency in Hz
BPFO	Ball Pass Frequency of outer race in Hz
BPFO	Ball Pass Frequency of Inner Race in Hz
CF	Crest Factor
CBM	Condition Based Maintenance
Da_c	Damage cost
Da_{tc}	Total Damage Cost
Do_{tc}	Total Downtime Cost/year
Do_c	Downtime cost
FTF	Fundamental Train Frequency
f	Frequency of planned stoppage
GMF	Gear Mesh Frequency
I	Gearbox ratio
L_c	Labor cost
L_{tc}	Total Labor cost/year
M_c	Material cost
M_{tc}	Total material cost/year
Nb	Number of rolling elements
N	Number of point in time domain
n_{pc}	No. of craftspeople for planned maintenance
n_{uc}	No. of craftspeople for unplanned maintenance
Pd	Pitch diameter in mm
PM	Preventive Maintenance
PV	Peak value
RMS	Root Mean Square
Rd	Roller diameter in mm
R_{Da}	Risk consequence of damage
RTF	Run To Failure
R_b	Risk consequence of breakdown
S	Relative Speed in rev./sec
T_{pr}	Planned Repair time
T_{ur}	Unplanned Repair time
T_d	Downtime in hours
V	Machine linear speed
Z	Gear Tooth count
Θ	Contact angle in degree
λ	Failure rate

INTRODUCTION

Vibration measurement using different signal processing with suitable set-up data is a powerful tool to identify and predict failure. Conducting different Vibration analysis techniques could lead to improve Machine Health and availability. Paper Machine faults and malfunctions can take place at any time, due to several causes such as structure resonance, rolls drive systems, rolls supported bearings and rolls nip interaction. Paper machine has a wide range of rotor-bearing applications; one of its most important configuration is Forming Roll at the first stage of formation. Increased vibration at any rolls faulty bearings could be transmitted through machine structure or rolls nip interaction that has an impact on tissue paper quality. The Present study focused on Forming Roll Faulty Bearing and its severity progress. Tracking fault progress can be carried out using different analysis techniques such as spectrum, time waveform, and impact demodulation for best fault diagnosis, decision-making, planning work, Machine Health and availability.

Costain [1] Studied Paper Machine faults through various vibration problems, but he focused on Forming Roll drive system, while the present study is focusing on Forming Roll supported bearings. Paper Machine Health and availability could be affected by process quality performance or vibration level. Paper Machine Process quality performance and its turbulence root causes identification using online quality control system is presented by Chioua et al. [2], while the present study is dealing with vibration measurement and analysis as a powerful tool to increase Machine Health and availability. An intelligent fault diagnosis system starting from data acquisition, followed by feature extraction, fault detection and identification is presented by Aherwar et al. [3] , they focused on gearbox fault detection and diagnosis using different vibration analysis techniques, while Rezaei [4] presented bearings failure types, fault detection, diagnosis and analysis techniques. Also Riaz et al. [5] presented vibration fault extraction and analysis techniques for rotating machinery. Fault feature extraction techniques were divided into three main categories Time Domain, Frequency Domain and Time Frequency Domain. To analyze Paper Machine signals for variable speed conditions; first order frequency 1X Peak should be selected based on machine drive speed calculation this process is called normalization. Abboud et al. [6] studied order-frequency tracking through spectral correlation and fast estimator of cyclic modulation spectrum. In the present study order frequency tracking is done through expert system to automatically adjust all graphs based on 1X peak selection.

Abboud et. al. [7] presented vibration analysis technique dealing with random and repetitive signatures which is named Square Envelope Specturm “SES”. This technique is useful for variable speed condition such as paper machine. Taylor [8] presented a practical guide for vibration analysis techniques which is applicable for rotating machinery. Hudson [9] presented another vibration analysis technique based on highest crest factor events identification in waveform that is called impact Demodulation. This technique could be used as an indicator of higher fault severity.

The present study is dealing with varaity of post processing techniques for fault detection and diagnosis to improve maintenance planning efficiency, Machine Health and Availability. Availability and Maintenance strategies had been listed by Mobley [10], while Mbowa et al. [11] focused on maintenance strategies effectiveness evaluation. Idhammar [12] addressed cost calculations based on risk consequences for Maintenance Strategies. The present study set formulas, as shown in Equations (from 10 to13) to be applicable for cost calculations of any selected maintenance strategy. The study has proven that Condition based Maintenance is the most cost-effective strategy.

In practical world, modeling of such complex system is too difficult; the present study is using vibration signal processing and analysis to detect faulty bearing as an indicator of its dynamic characteristics change. Recording of Paper Machine operating conditions plays a major role to build up a reliable data for analysis. Machine speed is related to process quality performance or vibration level. It's needed to set speed for data Acquisition process by selecting (1x) peak to transform the non-stationary signals into signals characterized by purely stationary properties this process is called normalization. Bearing frequencies formulas are listed by Felten and Graney et al. [13] and [14]. In the present study Forming Roll bearings faults have taken place after 5 years from start-up. Three Measurements (A, B and C) are conducted to study and track forming roll faulty bearings from fault detection phase till corrective actions. Measurement (A) before correction, measurement (B) after exchanging drive side bearing and measurement (C) after exchanging non-drive side bearing as shown in Fig.4.

CASE STUDY ON TISSUE PAPER MACHINE FORMING ROLL:

To Study Forming Roll faulty bearings through vibration monitoring of both drive and non-drive sides, the machine is shown in Fig. 1 and Fig. 2 and placed in a Factory located in Sadat city, Egypt.

Description

An electric Motor of (200 kw) and (1490 rpm) fixed on bearing (6319 C3); drives gearbox with ratio (0.25). The gearbox is fixed on bearings (3313) and (3218) for high and low speed shafts. The power is transferred by cardan shaft to Forming Roll Supported bearings (23052 CCK/W33).

Instrumentations

A schematic diagram for instrumentations set up process is shown in Fig.3:
- Tri-Axis Accelerometer for the vibration pickup.
- Analyzer for vibration data collection and signal analysis.
- Computerized Vibration Analysis “Expert system”.

Data Acquisition Procedure

The location and orientation of each measuring point is selected based on stiff location, Close to bearings, Safe and far from high temperature or magnetic field or chemicals or water or steam. Sketch for measuring points and orientations is shown in Fig.5, where RAT means Radial in z-axis, Axial in x-axis, Tangential in y-axis. So that it can provide the measuring system with information needed to the vibration analysis. Another needed data is listed in Table 2 such as relative speed for each point and its bearing number in order to calculated bearing fault frequencies.

Signal Processing

The Nature of Electronic Signals is divided into three main categories:
- Static and quasi-static; unchanged over a long period of time.

- Periodic and Repetitive Signals; repeated on a regular basis including harmonics signals.
- Transient and Quasi Transient Signals; one time pulsed or periodically but with a short duration.

All continuous periodic signals could be represented by a fundamental frequency sine wave using Fourier series. The signals are generated using sampling digital representation by Analog to Digital Converter (ADC) and filtered through High Pass, Low Pass and Band Pass process. Overlapping process is required if FFT time calculation is shorter than the time record length. The FFT algorithm, operating on N samples of time data produces N/2 frequency lines. The resolution in the time domain depends on the sampling rate of the D/A converter in the analyzer. The higher the sampling rate, the greater the resolution. FFT requires that the sampling rate has to be (2.56) times the maximum frequency. If actual signal is higher in frequency than the sampling frequency this can lead to gross errors and data loss if not avoided, that is called Aliasing. To avoid Aliasing the input signal should pass through an analog low-pass filter whose cut-off frequency is less than one-half the sampling frequency which is called anti-aliasing filter. Hanning window is used during sampling process to force the beginning and end of the time record to zero amplitude.

The following data are submitted during set-up phase: Low frequency range “100 Hz, Resolution 1600, 4 averages”, High frequency range “1000 Hz, Resolution 3200, 4 averages”, Cut-off frequency “0.2 Hz”, Transducer “type Accelerometer, Sensitivity 100 mv/g”, Vibration units “mm/sec”, Average overlap percentage “50%”, Window Type “Hanning”, Band Pass Filter “5000 - 10000 Hz”. Impact Demodulation cut-off frequency “10 Hz”, vibration units “g’s”, Band Pass Filter “1000 Hz”.

Vibration Analysis Procedure

The first order frequency is selected based on the recorded drive speed which is called normalization process then features are extracted and the overall severity is obtained. The suitable scale of amplitude is selected from the available Linear and Logarithmic scales. The equations (from 1 to 9) are used during vibration analysis phase.[13], [14]

$$\mathbf{1XM} = \mathbf{1XN} / \mathbf{I} \tag{1}$$

$$\mathbf{1XN} = \mathbf{V} / \boldsymbol{\pi}\, \mathbf{D_{roll}} \tag{2}$$

$$\mathbf{GMF} = \mathbf{S} * \mathbf{Z} \tag{3}$$

$$\mathbf{FTF} = \frac{\mathbf{S}}{\mathbf{2}} * [\mathbf{1} - (\frac{\mathbf{Rd}}{\mathbf{Pd}} * \mathbf{Cos\theta})] \tag{4}$$

$$\mathbf{BSF} = \frac{\mathbf{Pd}}{\mathbf{2Bd}} * \mathbf{S} * [\mathbf{1} - (\frac{\mathbf{Rd}}{\mathbf{Pd}} * \mathbf{Cos\theta})^{\mathbf{2}}] \tag{5}$$

$$\mathbf{BPFO} = \frac{\mathbf{Nb}}{\mathbf{2}} * \mathbf{S} * [\mathbf{1} - (\frac{\mathbf{Rd}}{\mathbf{Pd}} * \mathbf{Cos\theta})] \tag{6}$$

$$\mathbf{BPFO} = \frac{\mathbf{Nb}}{\mathbf{2}} * \mathbf{S} * [\mathbf{1} + (\frac{\mathbf{Rd}}{\mathbf{Pd}} * \mathbf{Cos\theta})] \tag{7}$$

$$\boldsymbol{RMS} = \sqrt{\frac{\sum_{n=1}^{N}[A(n)]^2}{N}} \qquad (8)$$

$$\boldsymbol{CF} = \frac{PV}{RMS} \qquad (9)$$

RESULTS AND DISCUSSION

Vibration Measurement and analysis are conducted, as shown in Fig.4. During a scheduled measurement (A); all cited peaks were monitored for exciting faults frequencies referring to Table 1 and 2. Forming Roll bearing faults were detected and Vibration analysis techniques were conducted such as spectrum analysis, Time waveform and Impact Demodulation.

Using Spectrum Analysis Technique in Logarithmic Scale

Forming Roll bearings (BPFO) fault frequencies were noticed for both drive and non-drive sides. A peak was found at “52.90 Hz” when selecting it, many excited harmonics are appeared in high range frequencies. Referring to equation (7) and Table 2. (BPFO) is calculated and the frequency was equaled to “56.19 Hz”. So, the cited peak had a frequency shift below the calculated (BPFO), that means a change of its dynamic characteristic as a result of bearing increased clearance. Those faults were noticed in both drive and non-drive sides. (BPFO) cited peak was noticed at 52.88 Hz or 2.66X with many excited harmonics in the High range as shown in Fig.6 and Fig.7. Applying zoom windowing process, two side bands peaks were found around (BPFO) cited peak and separated by 4.94 Hz or 0.25X from the centered peak. The presence of side bands with frequency equaled to (1XN) around (BPFO) peak increases fault severity for both drive and non-drive side as shown in Fig.8. Spectrum analysis technique is useful to detect bearing faults and track the progress. The presence of excited harmonics, side bands and floor rising up increases the fault severity but, it couldn’t distinguish severity source location for two similar bearings for same application.

Using Time Waveform Analysis Technique in Linear Scale

A beating phenomenon was noticed for both drive and non-drive side mainly in Axial direction with peak level equaled “15.9931 mm/s”, RMS “7.3145 mm/s” and Crest Factor “2.180” as shown in Fig.9 and Fig.10. Applying zoom windowing option; repeated peaks were found separated by 0.02 seconds that was equaled to 51.2 Hz (2.58X) referring to (BPFO) fault as shown in Fig.11 and Fig.12. Time waveform is useful to detect bearing faults and tracking the progress, but it’s still needed to distinguish bearings fault severity source location that lead us to go through the following technique which is called Impact Demodulation.

Using Impact Demodulation Technique

Applying impact Demodulation technique where amplitude is measured by acceleration in (g’s) unit as shown in Fig.13. Drive side peak level was equaled “40 g’s” in average, max. peak level was around “85.8149 g’s”, RMS was “15.4472 g’s” and Crest Factor was “5.555”. While Non-drive side peak level was equaled “2 g’s” in average, max. peak level was “7.6477 g’s”, RMS was “2.2407 g’s” and Crest Factor was “3.413 g’s” as shown in Fig.14. Referring to Impact Demodulation Alert level and comparing it with standard values mentioned by Hudson [8] related to drive speed, it’s noticed that the fault severity of Drive Side Bearing is higher than Non-Drive Side Bearing. Impact Demodulation technique can distinguish fault severity of two similar bearings as shown in Fig.13 and Fig.14. This technique support decision making, planning phase and reduce downtime.

MAINTENANCE PLANNING AND SCHEDULING

Planning and Schedule

A planned shutdown around 3 hours related to process “Felt change” was scheduled. After conducting measurement (A), all recommended corrective actions were listed to plan for both bearings exchange, the time needed was around 4 hours per each, materials were in place, resources were available, all needed data regarding mounting and dismounting procedures were in place. The maintenance planning was well prepared, while scheduling phase was divided into two planned shutdowns based on bearing fault severity.

Decision Making

After distinguishing the worst bearing by using Impact Demodulation technique, decision becomes easier. Instead of changing both bearings, the decision was to exchange only Drive Side Forming Roll Faulty Bearing after 2 days from measurement (A) during “Felt change” shutdown. Applying continuous condition monitoring of the other side bearing till next planned shutdown within 2 months. The Impact Demodulation technique extends components life time, improves machine health and availability.

Execution

After execution, the removed faulty bearing was inspected visually. It was found an excessive wear in its outer race as shown in Fig.15.

MACHINE HEALTH AFTER CORRECTION

Drive Side Forming Roll Bearing was exchanged during “Felt change” planned shutdown. A second measurement (B) was conducted to review the machine health after correction. Using spectrum analysis technique, it was noticed that the fault was disappeared, overall level was going down. Using impact Demodulation, the peak level went down from “40 g’s” to “0.4 g’s” in average” as shown in Fig.16. While Non-Drive Side still under continuous condition monitoring; a slight increase (from 2 to 3 g’s) was noticed using impact demodulation technique. During next scheduled shutdown after two months; the non-drive side bearing was exchanged and followed by the third measurement (C). Using impact demodulation technique to check machine health condition, it was noticed that the peak level went to zero. A Comparison among three conducted measurements (A, B, C) using all techniques. As shown from Fig.17 to Fig.20 machine health was improved after correction through vibration level reduction. Impact Demodulation technique after correction is reflecting machine health resulted by around 100% vibration Impact reduction.

DESIGN OUT MAINTENANCE

Maintenance Strategies Cost comparison based on risk consequences are conducted as follow:

- **Direct Maintenance cost/year "Labor + Material":**

$$\boldsymbol{L_{tc}} = (\boldsymbol{L_c} * \boldsymbol{T_{pr}} * \boldsymbol{n_{pc}} * \boldsymbol{f}) + (\boldsymbol{\lambda} * \boldsymbol{L_c} * \boldsymbol{T_{ur}} * \boldsymbol{n_{uc}} * \boldsymbol{R_b}\%) \quad (10)$$

$$\boldsymbol{M_{tc}} = (\boldsymbol{M_c} * \boldsymbol{f}) + (\boldsymbol{M_c} * \boldsymbol{R_b}\%) \quad (11)$$

- **Downtime cost/year:**

$$\boldsymbol{Do_{tc}} = (\boldsymbol{\lambda} * \boldsymbol{Do_c} * \boldsymbol{T_d} * \boldsymbol{R_b}\%) \quad (12)$$

- **Cost of Possible damages/year:**

$$\boldsymbol{Da_{tc}} = (\boldsymbol{\lambda} * \boldsymbol{Da_c} * \boldsymbol{R_b} * \boldsymbol{R_{Da}}\%) \quad (13)$$

To calculate Total Maintenance Annual Cost, all previous equations (from 10 to13) were used for each maintenance strategy:

Run to failure (RTF):
Given data:$\lambda = 0.2$, $R_b = 100\%$, $T_{ur} = 12\ hr$, $n_c = 4$, $L_c = 1\$$, $M_c = 3369\$$, $Do_c = 3000\$$, $T_d = 14\ hrs$, $R_{Da} = 50\%$, (Da_c) = 50000$
Applying equation (10), we get: $L_{tc} = 0.2 * 100\% * 12 * 4 * 1 = 9.6\$$
Applying equation (11), we get: $M_{tc} = 0.2 * 3369$ *100% = 673.8$
Applying equation (12), we get: $Do_{tc} = 0.2 * 3000 * 14 * 100\% = 8400\$$
Applying equation (13), we get: $Da_{tc} = 0.2 * 50\% * 100\% * 50000\$ = 5000\$$

Preventive Maintenance (PM):
Given data:$f = 1$, $R_b = 5\%$, $T_{pr} = 8\ hr$, $n_{pc} = 2$, $L_c = 1\$$, $n_{uc} = 4$, $T_{pr} = 12\ hr$, $M_c = 3369\$$, $Do_c = 3000\$$, $T_d = 14\ hrs$, $R_{Da} = 50\%$, (Da_c) = 50000$
Applying equation (10), we get: $L_{tc} = 0.2 * 8 * 2 * 1 + 1\% * 12 * 4 * 1\$ = 34.4\$$
Applying equation (11), we get: $M_{tc} = 1 * 3369 + 5\% * 3369 = 3537.45\$$
Applying equation (12), we get: $Do_{tc} = 3000 * 14 * 5\% = 2100\$$
Applying equation (13), we get: $Da_{tc} = 5\% * 50\% * 50000\$ = 1250\$$

Condition Based Maintenance (CBM):
Given data:$f = 0.2$, $R_b = 1\%$, $T_{pr} = 8\ hr$, $n_{pc} = 2$, $L_c = 1\$$, $n_{uc} = 4$, $T_{pr} = 12\ hr$, $M_c = 3369\$$, $Do_c = 3000\$$, $T_d = 14\ hrs$, $R_{Da} = 50\%$, (Da_c) = 50000$
Applying equation (10), we get: $L_{tc} = 2 * 8 * 2 * 1 + 1\% * 12 * 4 * 1\$ = 32.48\$$
Applying equation (11), we get: $M_{tc} = 0.2 * 3369 + 1\% * 3369 = 707.49\ \$$
Applying equation (12), we get: $Do_{tc} = 3000 * 14 * 1\% = 420\$$
Applying equation (13), we get: $Da_{tc} = 1\% * 50\% * 50000\$ = 250\$$

The study has proven that Condition based Maintenance is the most cost-effective strategy. Total cost percentage of the three maintenance strategies RTF, PM, CBM are 62%: 32%: 6% as shown in Table 3 and Fig.21.

CONCLUSION

Using different vibration analysis techniques to support decision-making, increases availability and Machine health by reducing vibration impact around 100%.

- Spectrum analysis technique is useful to detect bearing faults and tracking the progress but, this technique couldn't distinguish the severity source location due to bearing similarity.
- Time waveform is useful to detect bearing faults and tracking the progress, but it's still needed to distinguish bearings fault severity source location.
- Impact Demodulation technique can distinguish fault severity of two similar bearings. The impact demodulation peak value of Drive side bearing was higher than Non-drive side. So, decision was to exchange the higher severity faulty bearing first and keep monitoring of the other bearing till next planned shutdown.
- Impact Demodulation technique improves maintenance planning efficiency, avoids any unplanned stoppage, improves machine health and availability.
- The study has proven that Condition based Maintenance is the most cost-effective strategy. Total cost percentage of the three maintenance strategies are 62%: 32%: 6% respectively.

For further study, the remaining components should be investigated. Extra variable operating parameters recommended to be studied for their impact on fault diagnosis and analysis.

REFERENCES

[1] A. Costain and B. Eng, "Case Studies on Paper Machine Vibration Problems", Bretech Engineering Ltd. Available: www.bretech.com. [Online].
[2] M. Chioua et al., "Plant-wide root cause identification using plant key performance indicators (KPIs) with application to a paper machine", Control Eng. Pract., vol. 49, pp. 149–158, (2016).
[3] A. Aherwar and S. Khalid, "Vibration analysis techniques for gearbox diagnostic: A review", Int. J. Adv. Eng. Technol., vol. 3, no. 2, pp. 4–12, (2012).
[4] A. Rezaei, "Fault Detection and Diagnosis on the Rolling Element Bearing", Ottawa-Carleton Institute, (2007).
[5] S. Riaz, H. Elahi, K. Javaid, and T. Shahzad, "Vibration Feature Extraction and Analysis for Fault Diagnosis of Rotating Machinery-A Literature Survey", Asia Pacific J. Multidiscip. Res., vol. 5, no. 51, pp. 103–110, (2017).
[6] D. Abboud and J. Antoni, "Order-frequency analysis of machine signals", Mech. Syst. Signal Process., vol. 87, no. September 2016, pp. 229–258, (2017).
[7] D. Abboud, J. Antoni, S. Sieg-Zieba, and M. Eltabach, "Envelope analysis of rotating machine vibrations in variable speed conditions: A comprehensive treatment", Mech. Syst. Signal Process., vol. 84, pp. 200–226, (2017).

[8] J. I. Taylor, The Vibration Analysis Handbook, 2nd ed. Vibration Consultants, (2003).

[9] Steven Hudson, “Impact Demodulation With Expert ALERT Software on TRIO, DC, DCA and Sprite Data Collectors”, Technology, Product Engineering, Azima DLI. Available: www.AzimaDLI.com. , [Online]. (2015)

[10] R. K. Mobley, "An introduction to predictive maintenance", 2nd ed. America: Butterworth-Heinemann, (2002).

[11] C. Mbohwa and B. Mwanza, “Evaluating Maintenance Strategies Effectiveness on Overall Equipment Utilization”, pp. 2323–2332, (2016).

[12] E. A. Idhammar, "Preventive Maintenance, Essential Care and Condition Monitoring", America: IDCON INC., (1999).

[13] D. Felten, “Understanding Bearing Vibration Frequencies”, Easa Currents, no. September, pp. 1–3, (2003).

[14] B. P. Graney and K. Starry, “Rolling element bearing analysis crosses threshold”, in Materials Evaluation, vol. 70, no. 1, pp. 78–85 , (2011).

FIGURES AND TABLES:

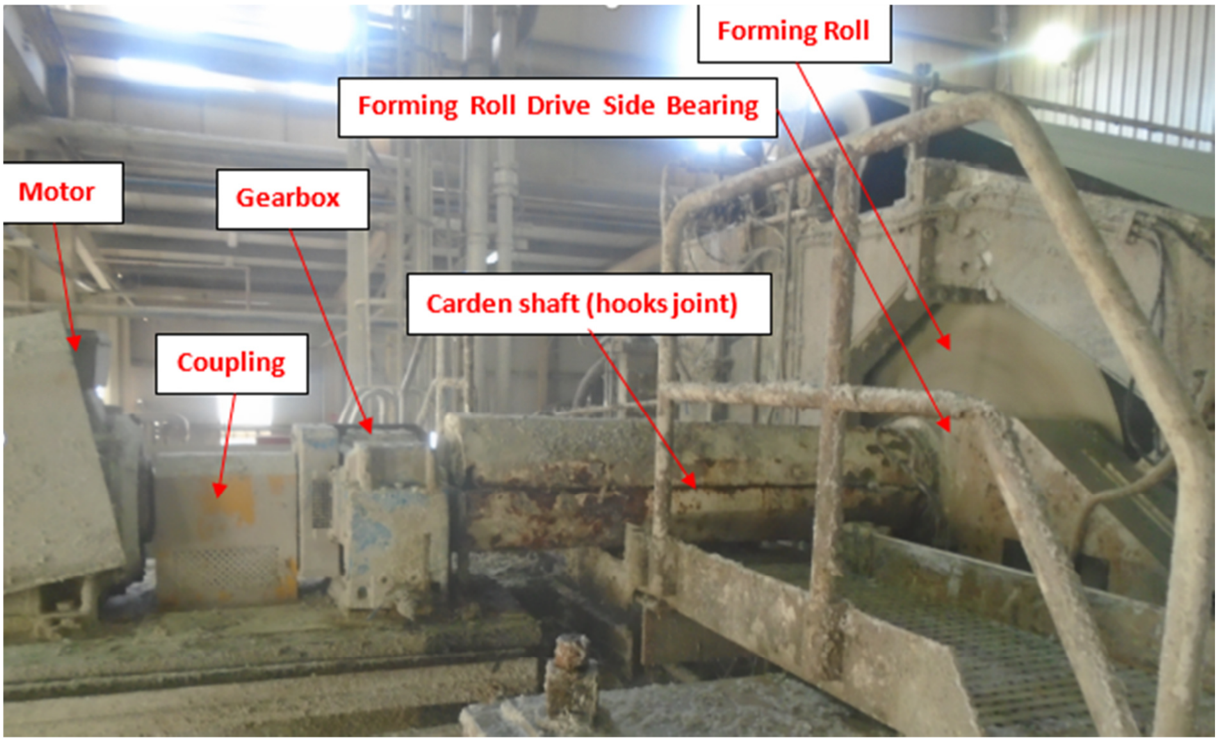

Fig. 1. Forming Roll Drive Side.

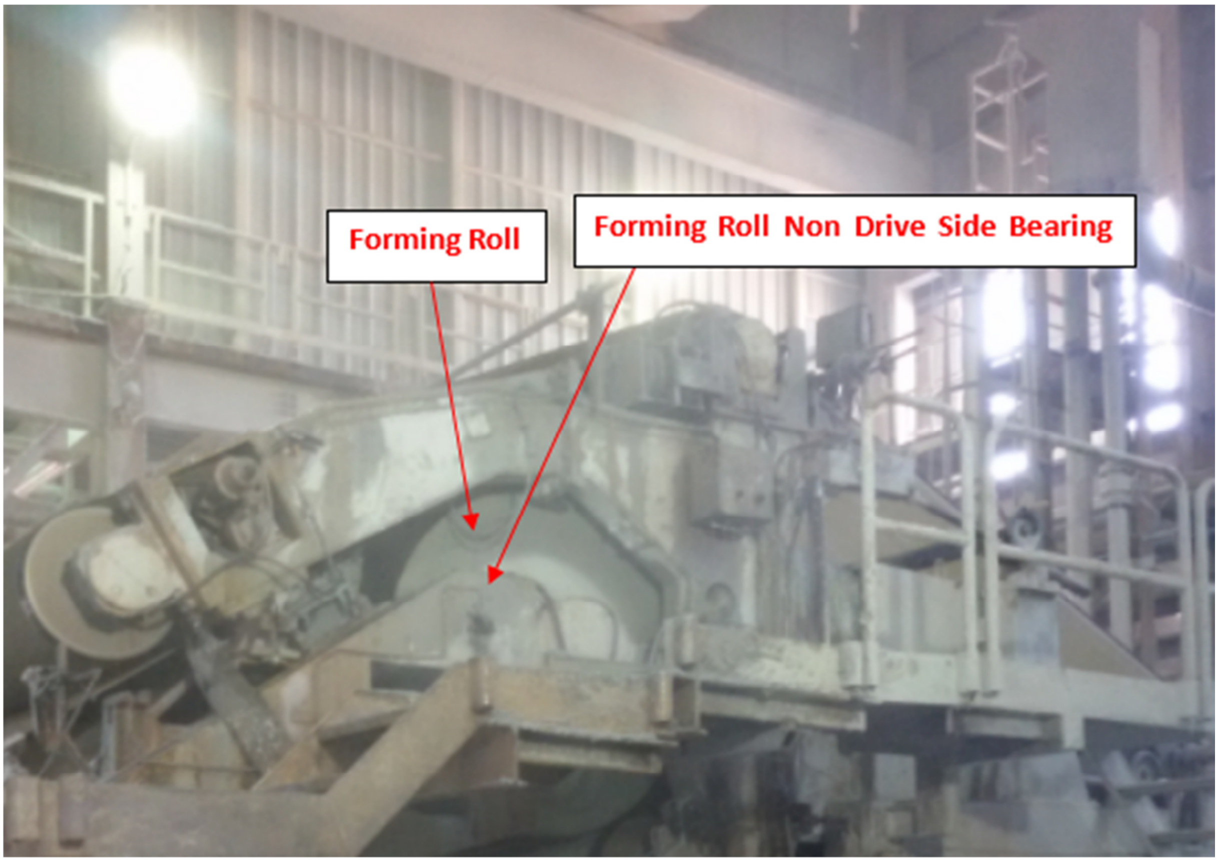

Fig. 2. Forming Roll Non-Drive Side.

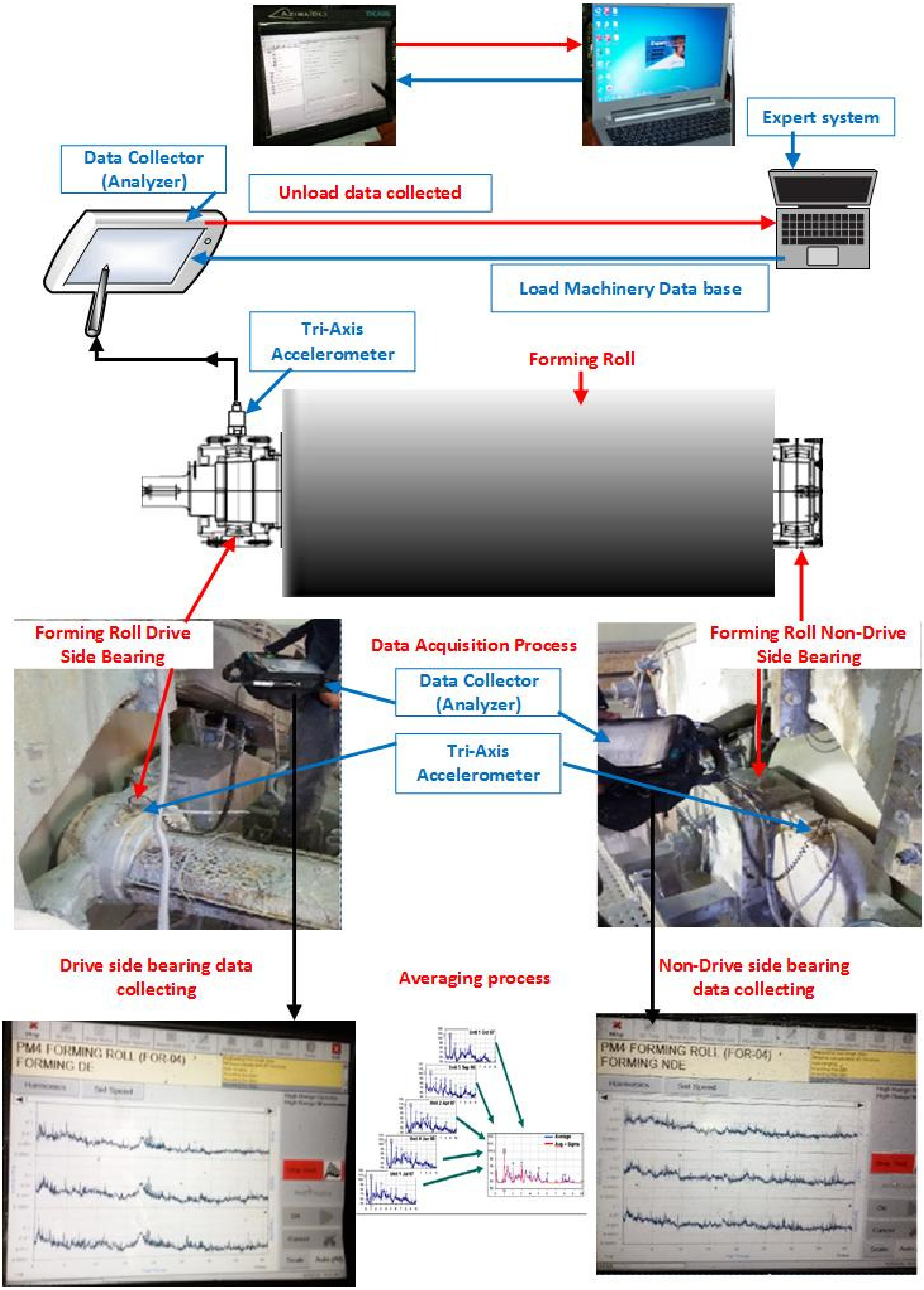

Fig. 3. A schematic diagram for instrumentations set up process.

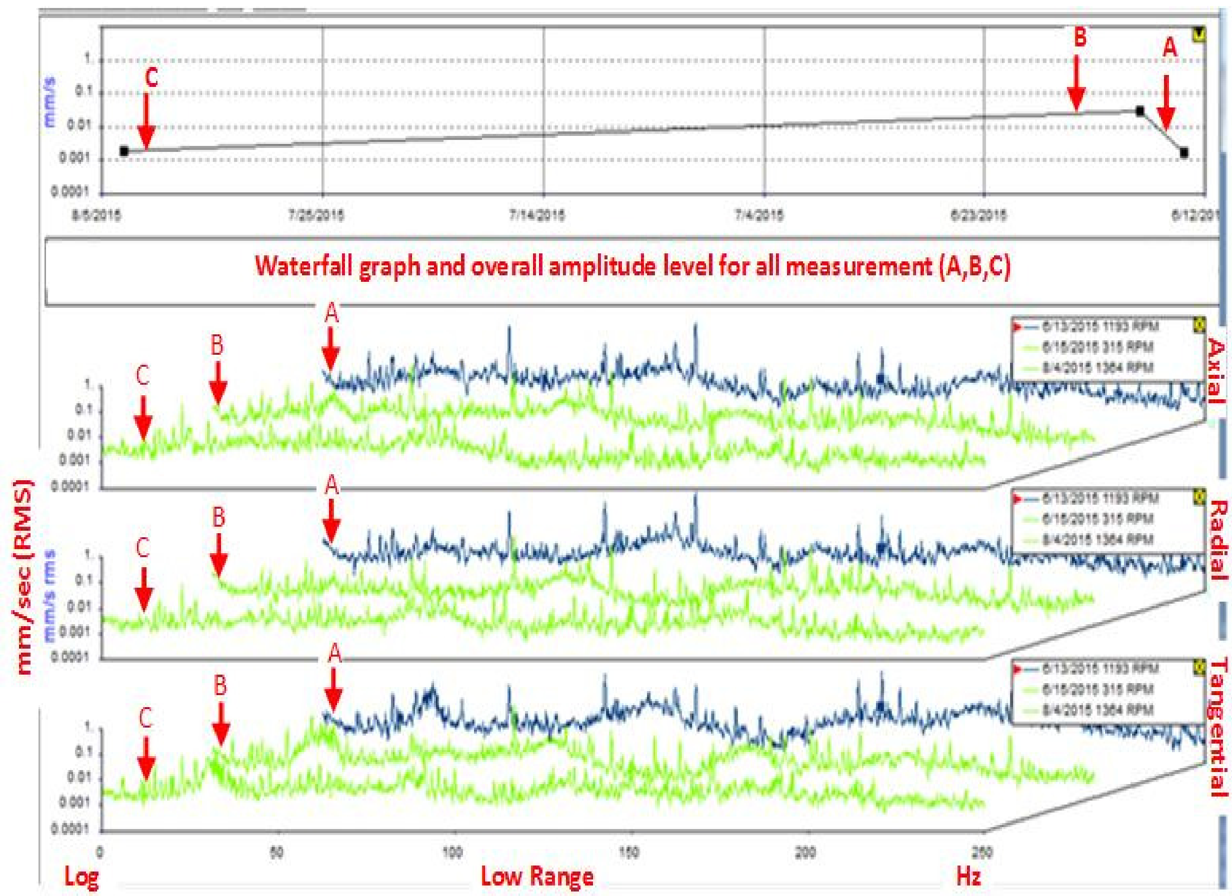

Fig. 4. waterfall graph and overall amplitude level for all measurements.

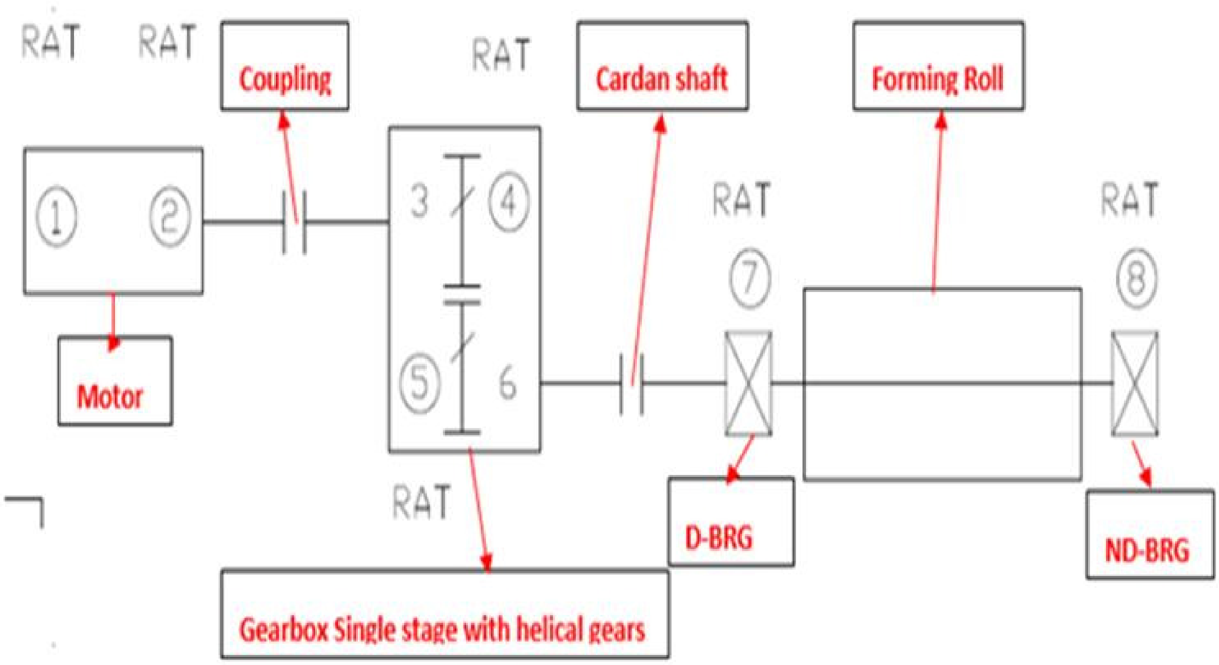

Fig. 5. Sketch for Forming Roll measuring points and orientations.

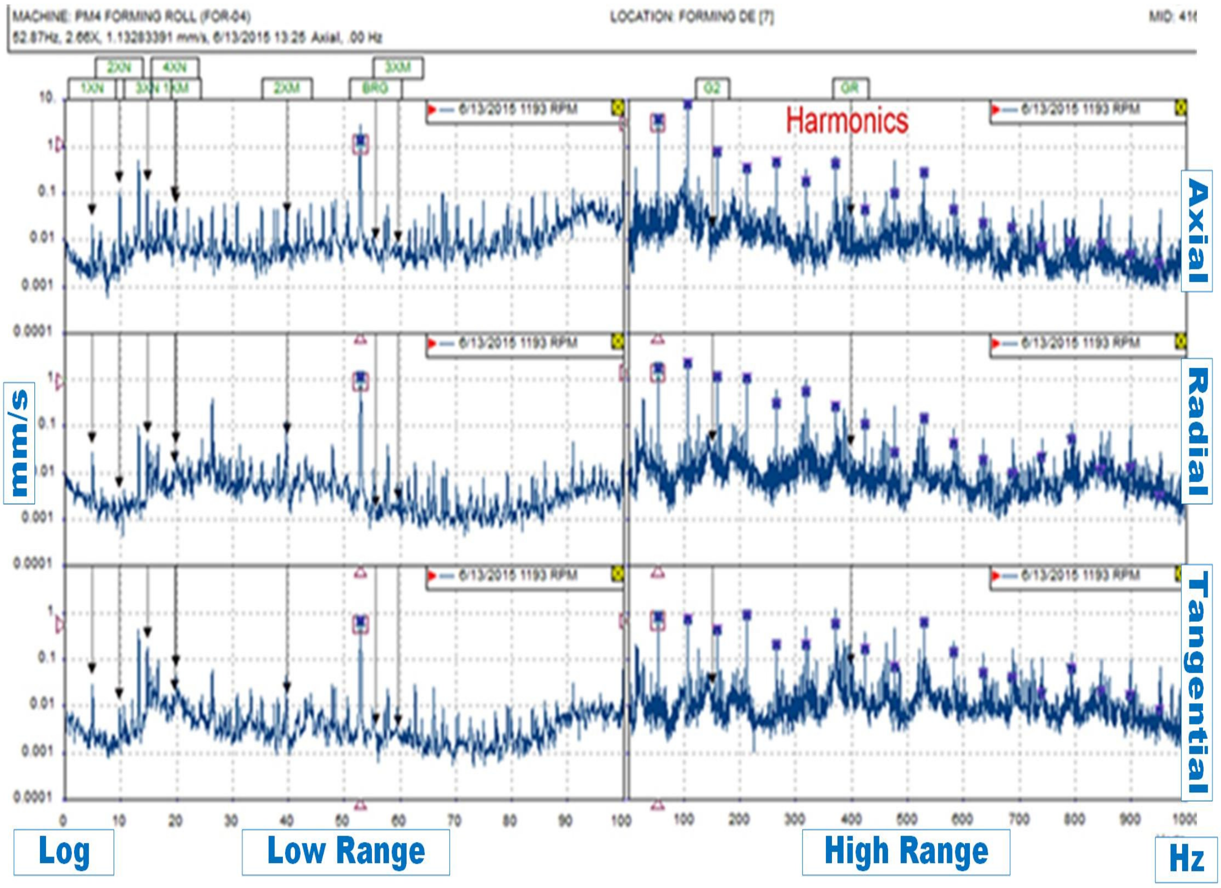

Fig. 6. Forming Roll Drive Side bearing spectrum graph.

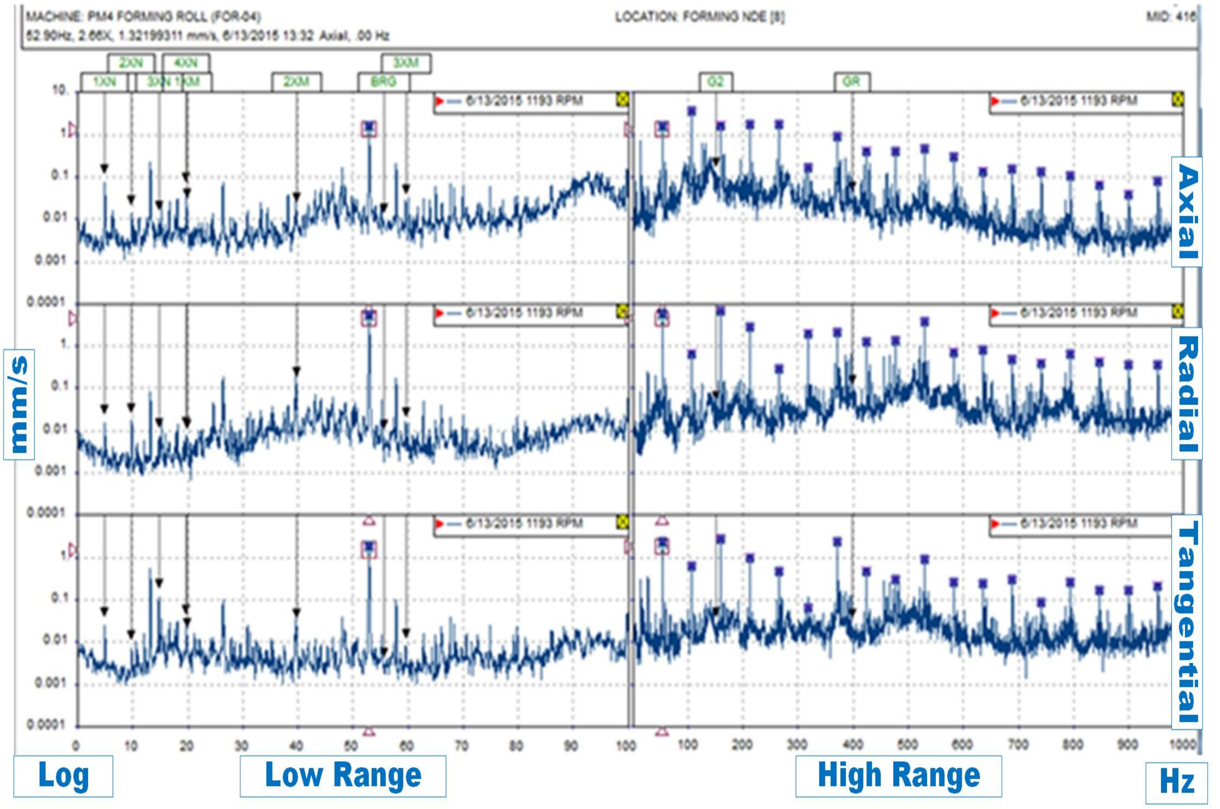

Fig. 7. Forming Roll Non-Drive Side bearing spectrum graph.

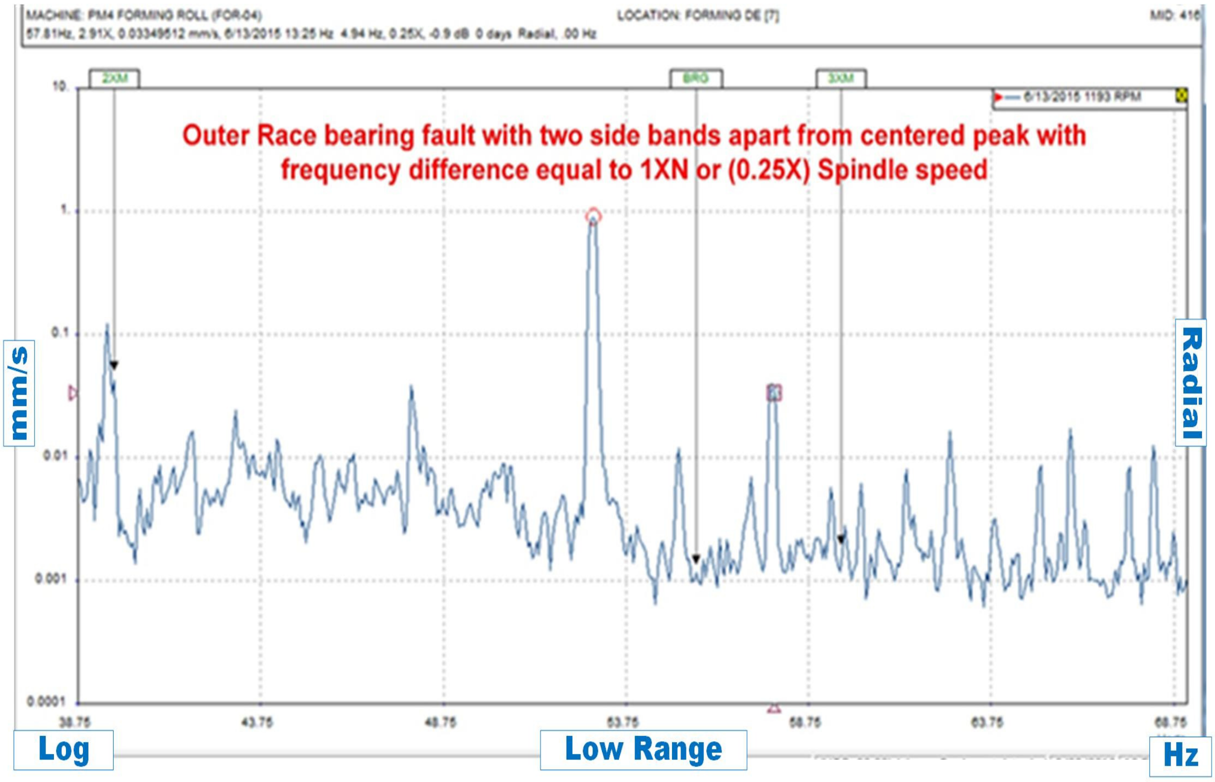

Fig. 8. Forming Roll Drive Side outer race bearing fault and its side bands after windowing.

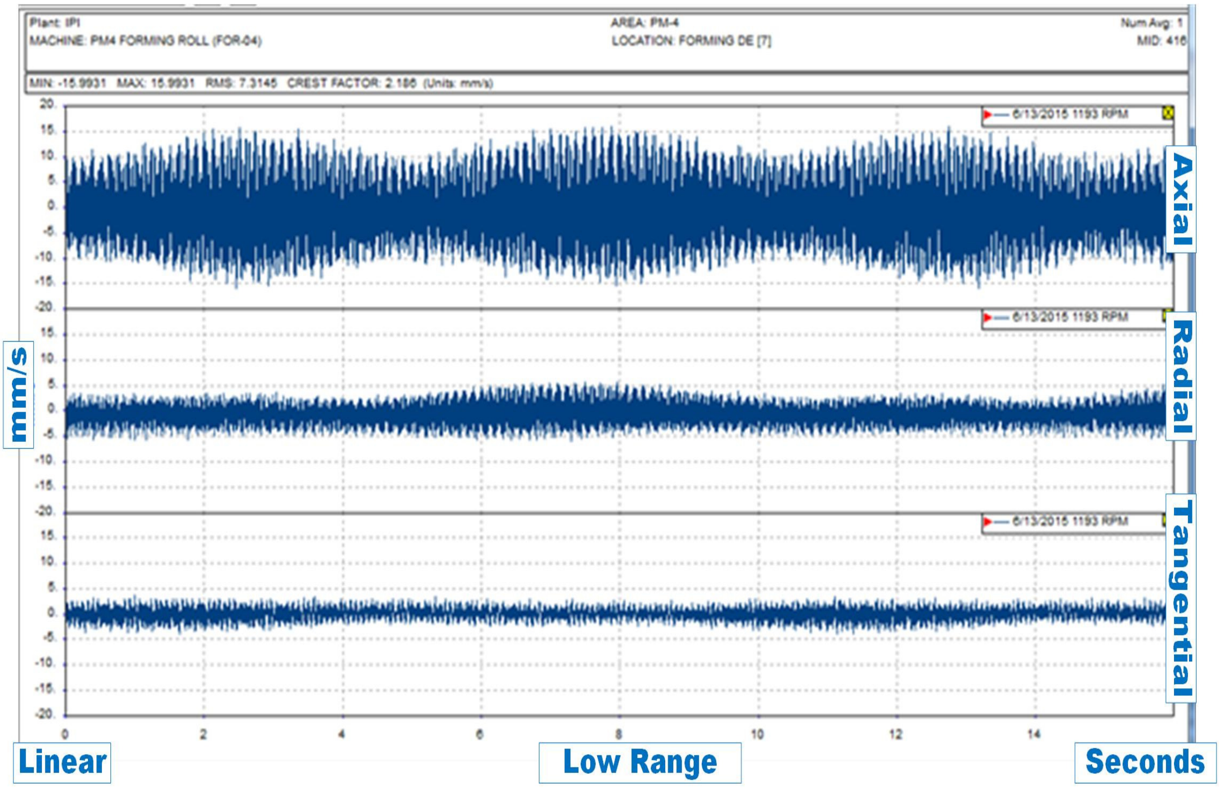

Fig. 9. Forming Roll Drive Side bearing Time waveform.

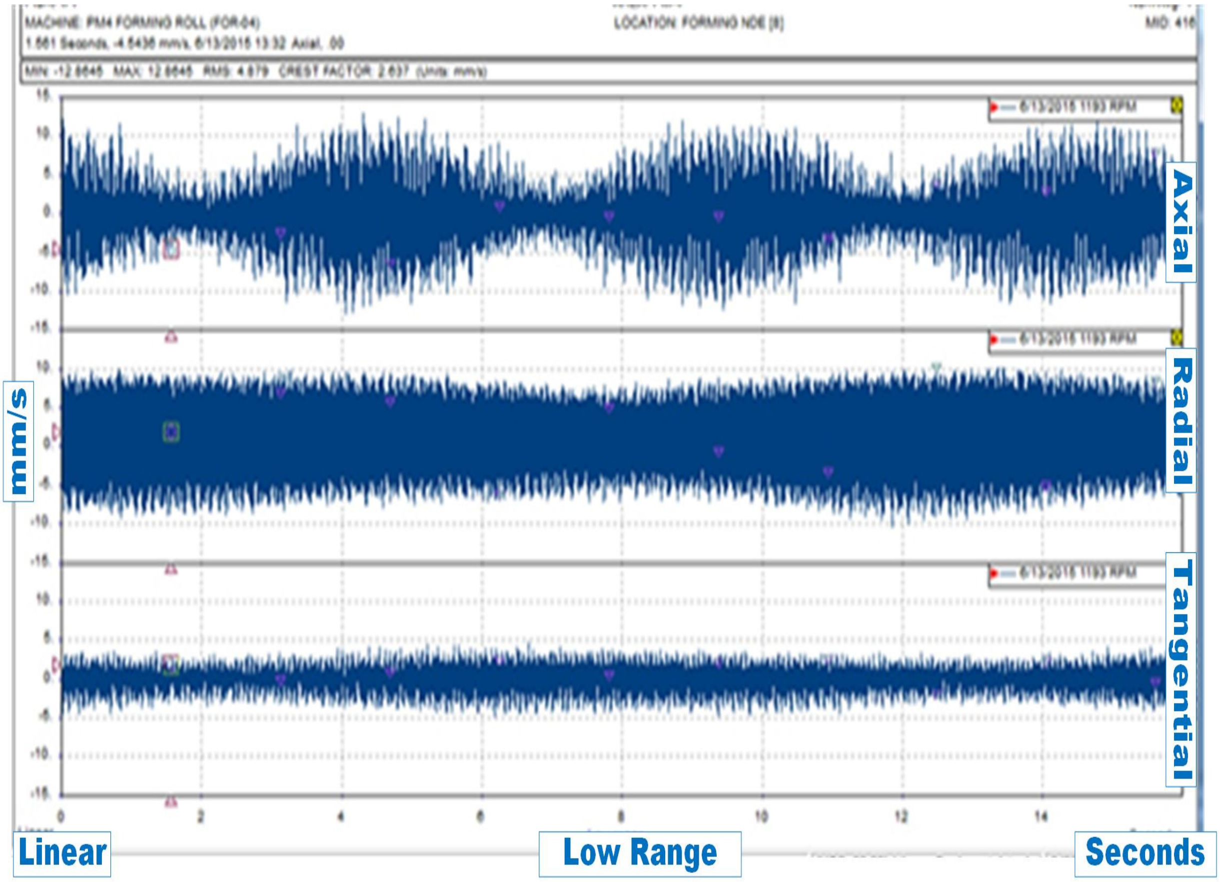

Fig. 10. Forming Roll Non-Drive Side bearing Time waveform.

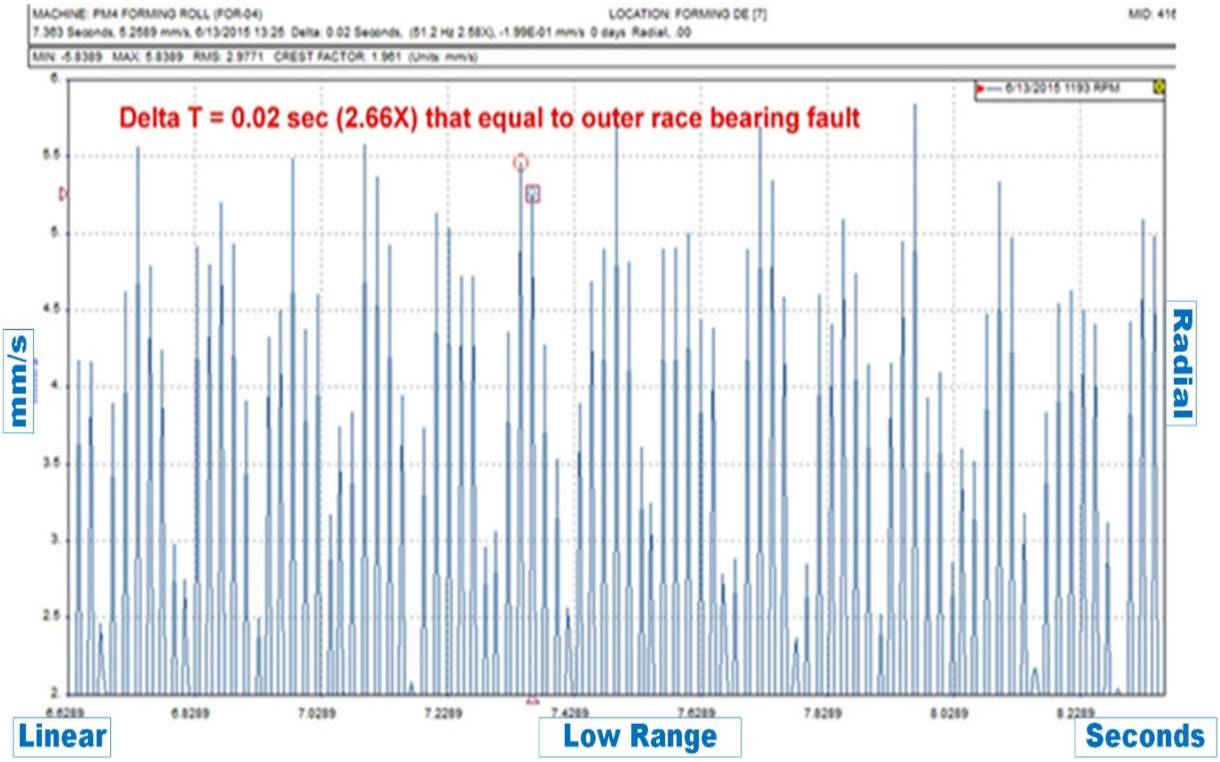

Fig. 11. Forming Roll Drive Side bearing Waveform after applying zoom windowing.

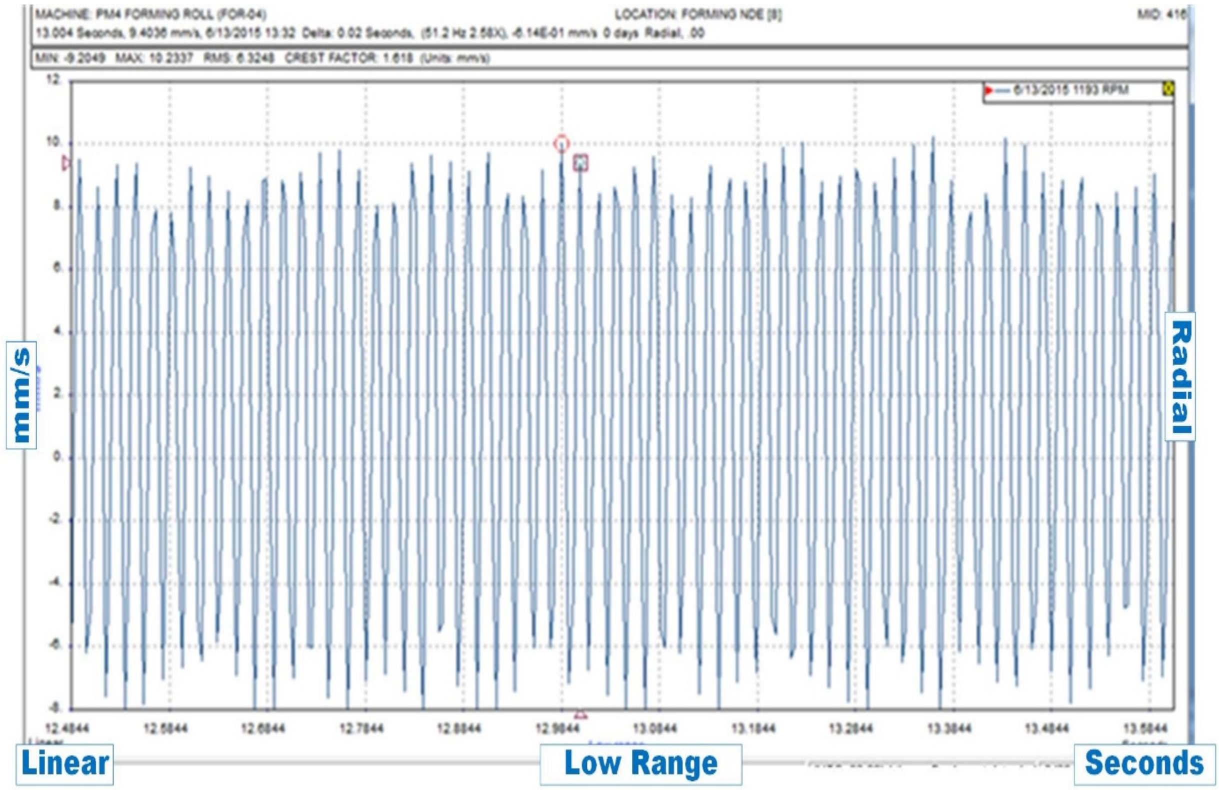

Fig. 12. Forming Roll Non-Drive Side bearing Waveform after applying zoom windowing.

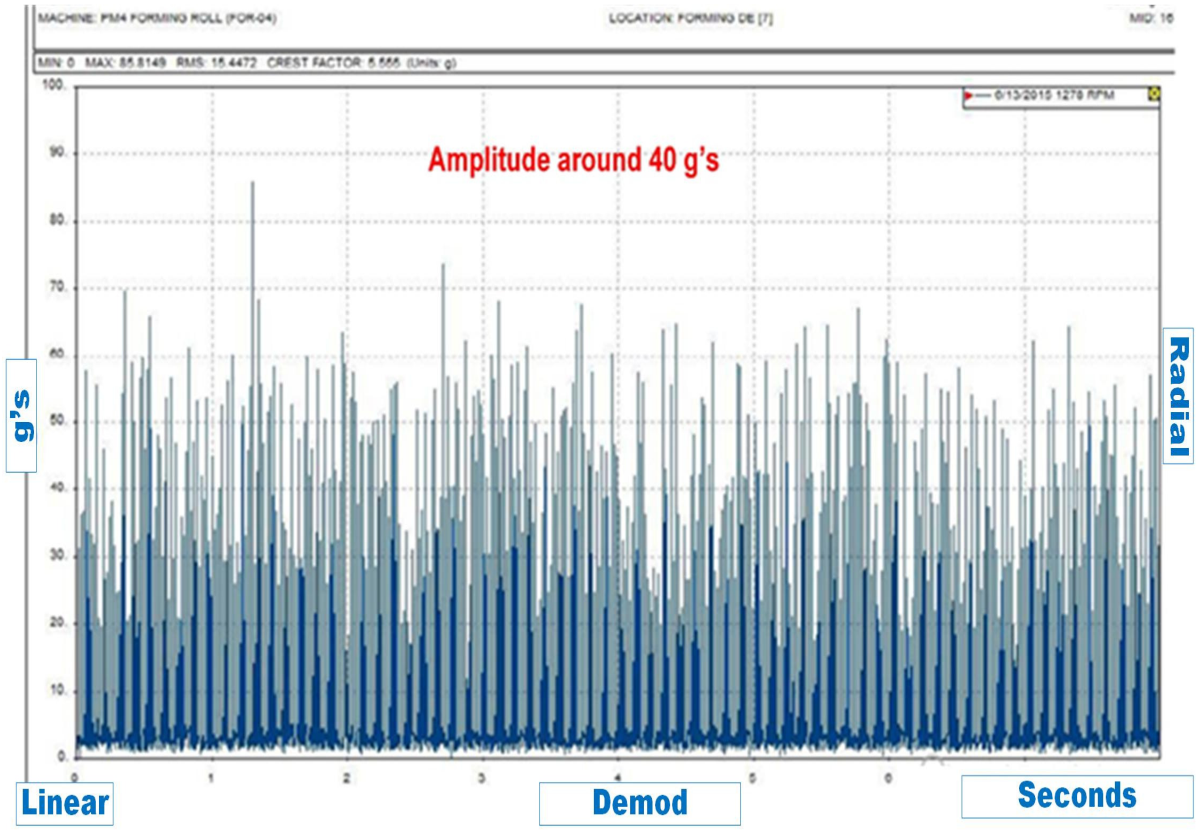

Fig. 13. Forming Roll Drive Side bearing Impact Demodulation before correction.

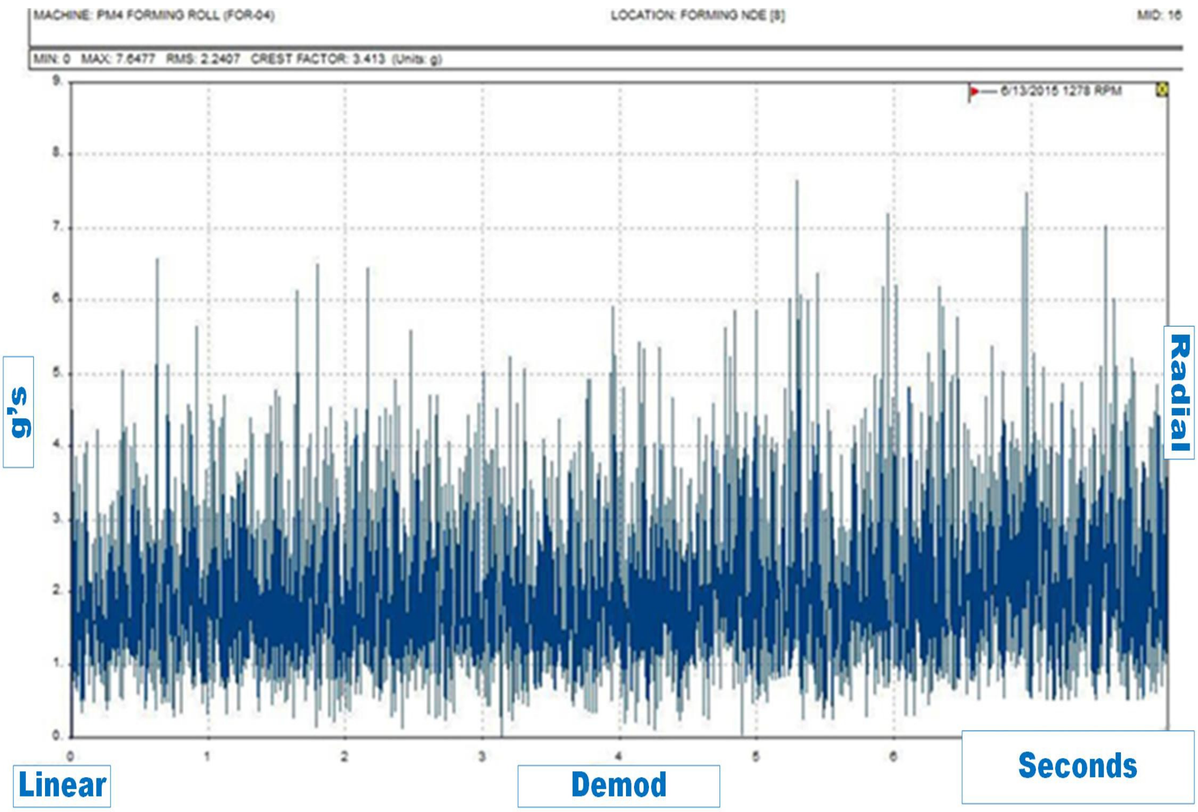

Fig. 14. Forming Roll Non-Drive Side bearing Impact Demodulation before correction.

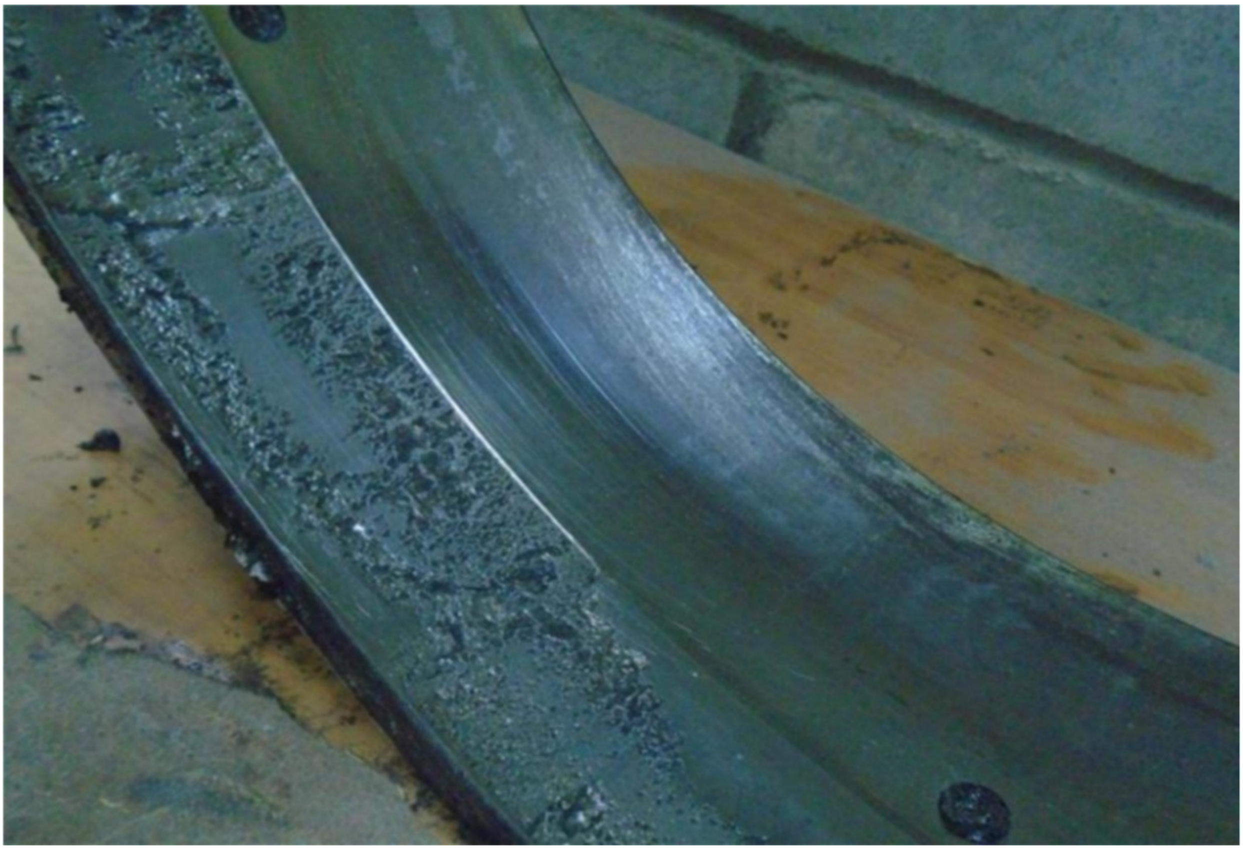

Fig. 15. Forming roll Drive Side bearing Outer Race Excessive Wear.

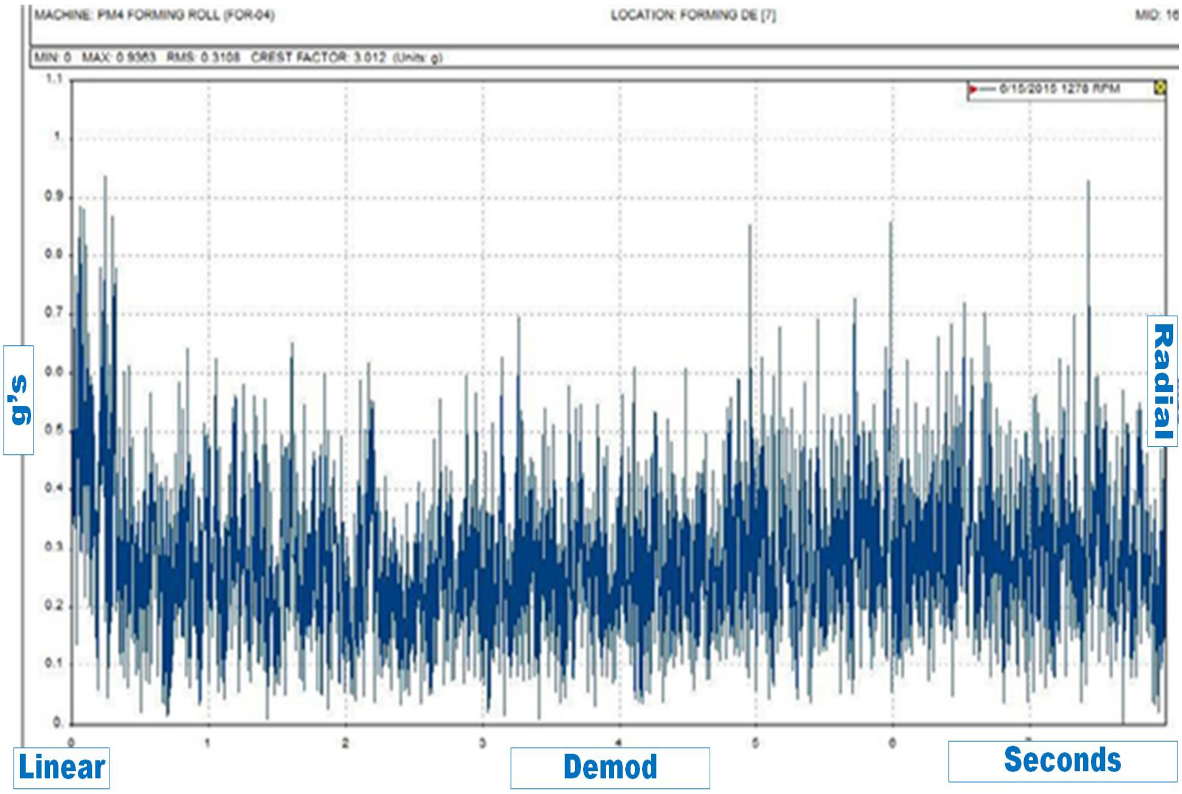

Fig. 16. Forming Roll Drive Side bearing Impact Demodulation after correction.

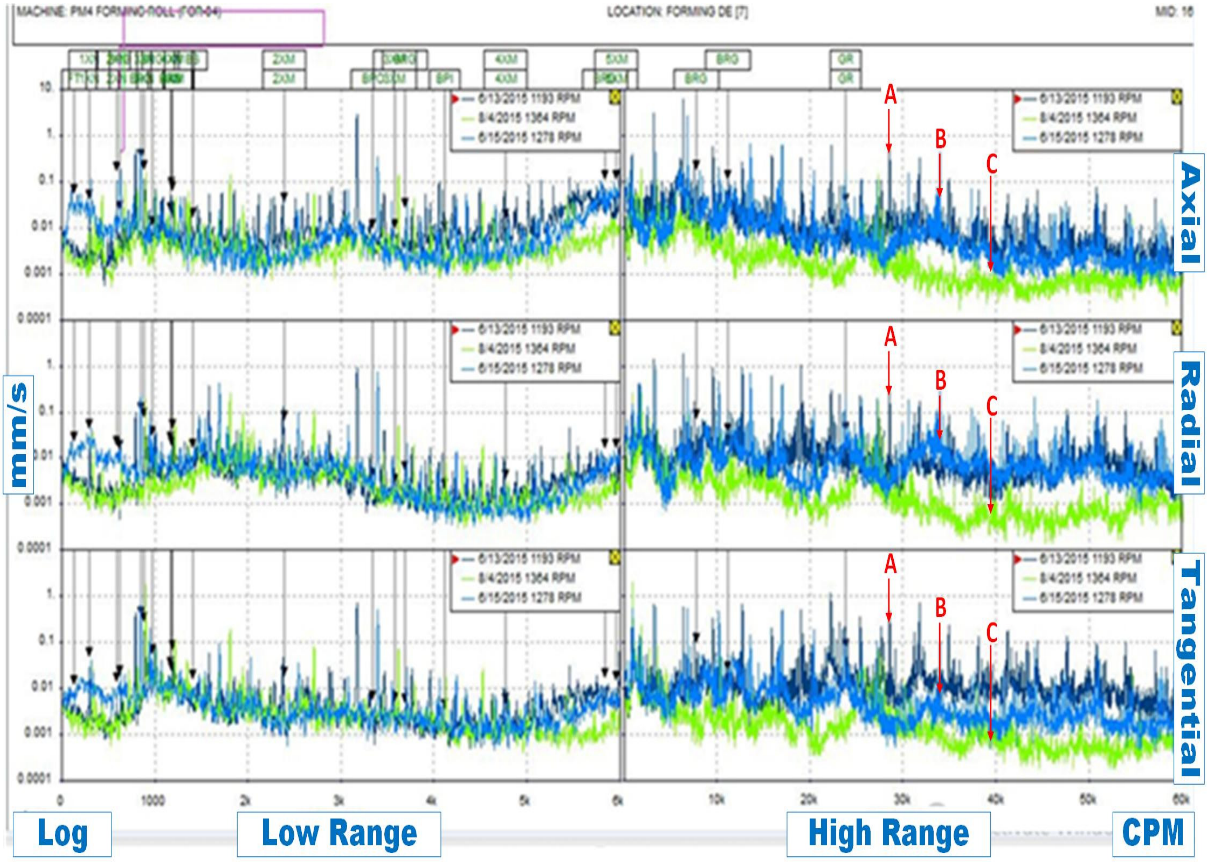

Fig. 17. Forming Roll Drive Side bearing Spectrum before and after correction Comparison.

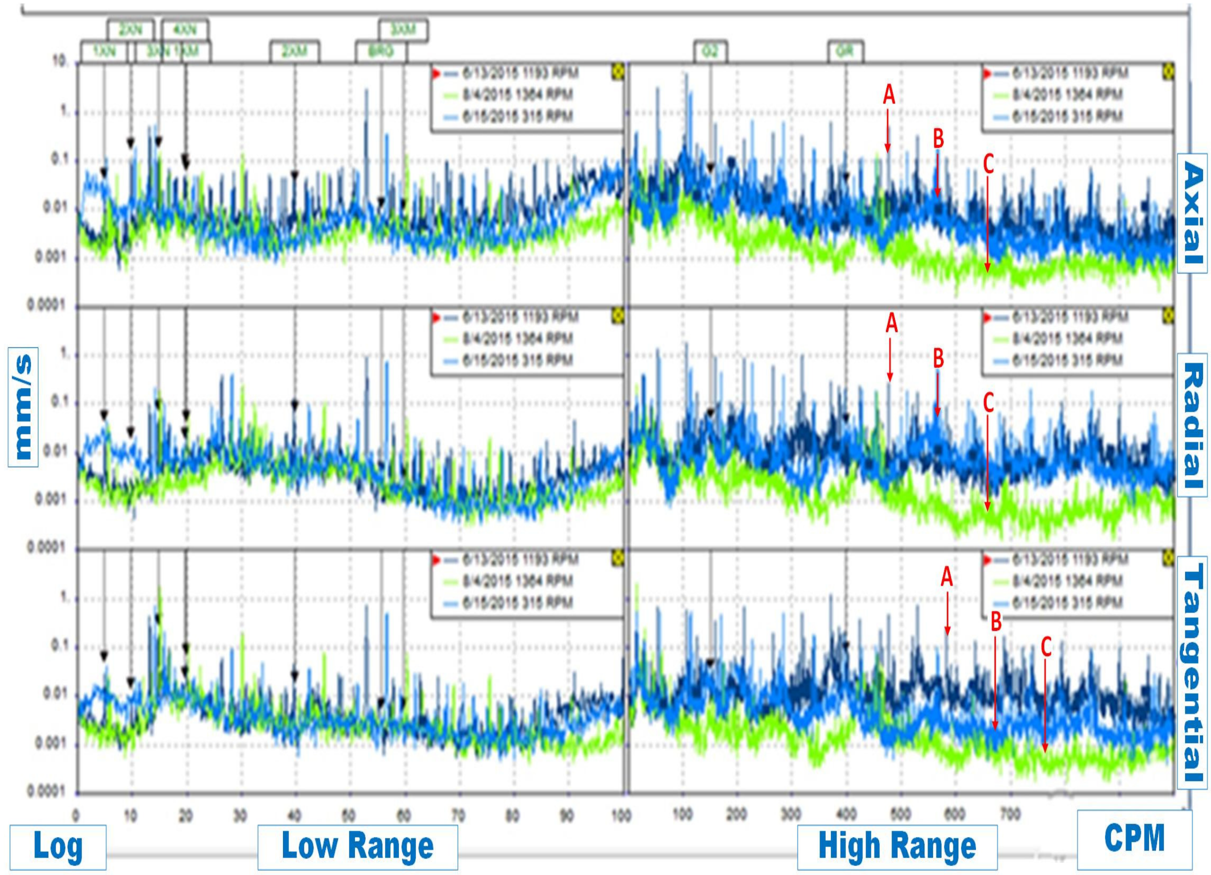

Fig. 18. Forming Roll Non-Drive Side bearing Spectrum before and after correction comparison.

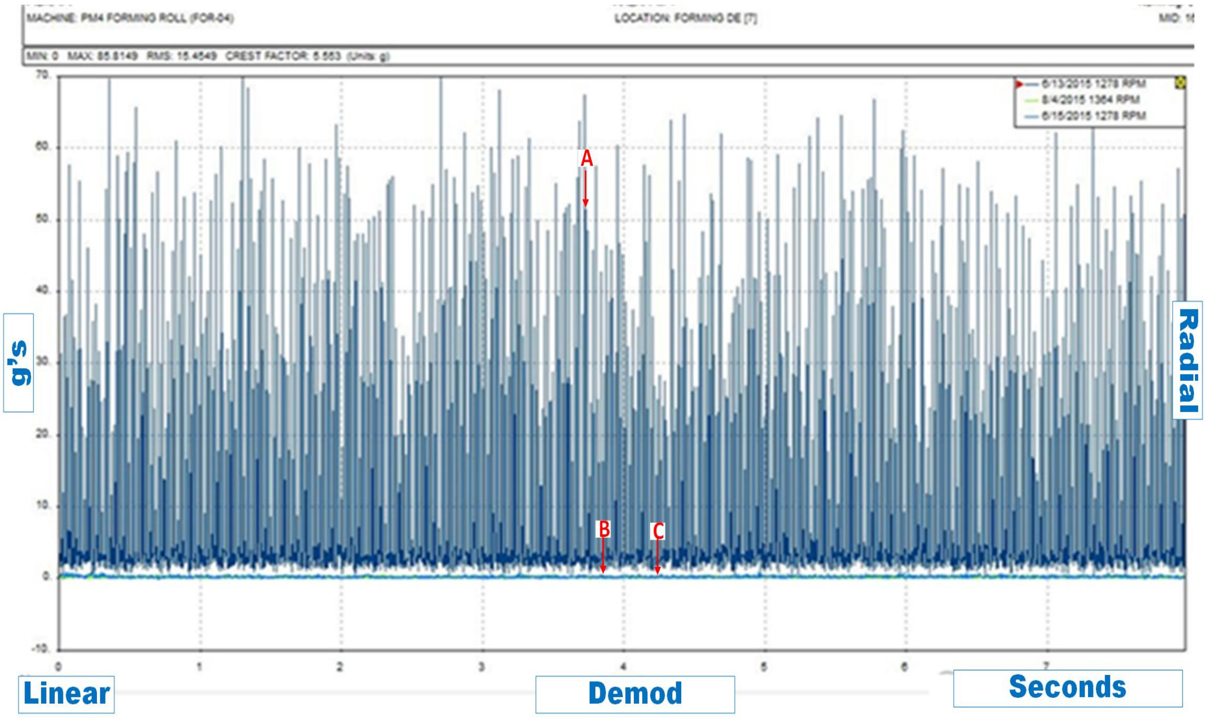

Fig. 19. Forming Roll Drive Side bearing Impact Demodulation before and after corrections comparison.

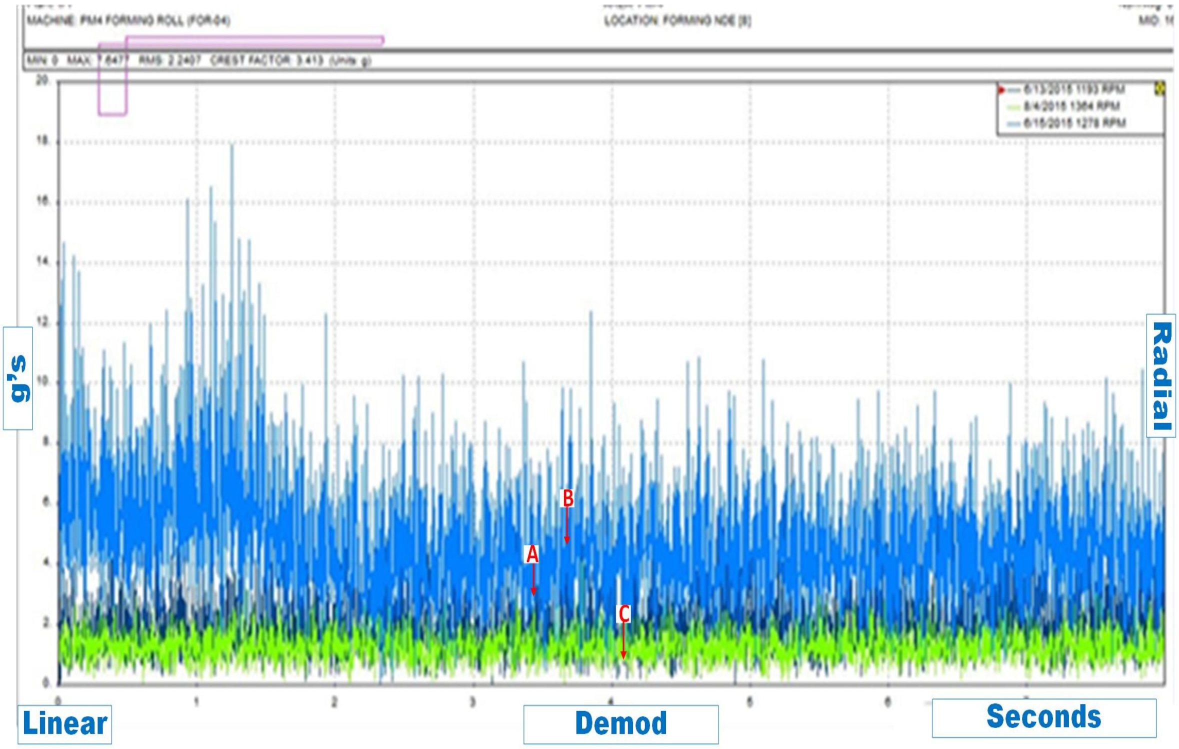

Fig. 20. Forming Roll Non-Drive Side bearing Impact Demodulation before and after corrections comparison.

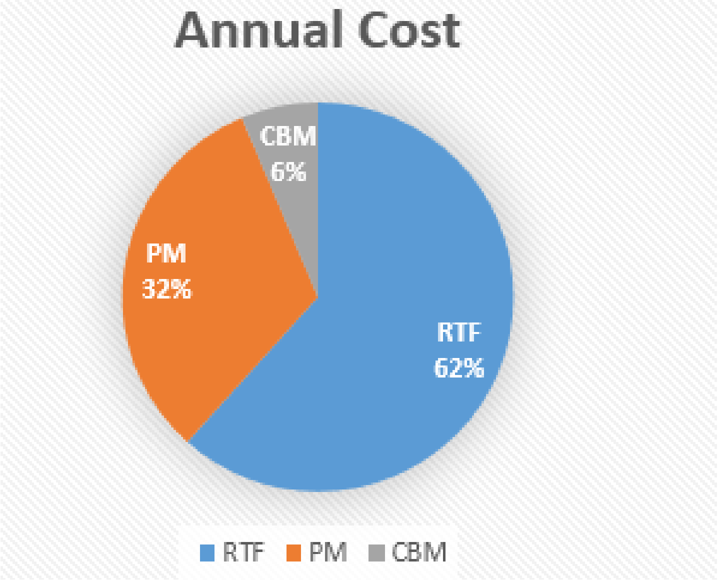

Fig. 21. Three maintenance strategies based on Risk Consequence Cost Calculations.

Table 1. Forming Roll Trouble Shooting Frequency Guide.

Code	Name	On Secondary	Elements	Final Ratio
1XN	1 x spindle shaft	Yes	1	0.2469
2XN	2 x spindle shaft	Yes	2	0.4938
3XN	3 x spindle shaft	Yes	3	0.7407
1XM	1 x motor shaft	No	1	1
2XM	2 x motor shaft	No	2	2
3XM	3 x motor shaft	No	3	3
GR	Main gear mesh	No	20	20
$\text{Motor}_{\text{RPM}}$ (1XM) = Roll_{RPM} / Gearbox Reduction Ratio, Roll_{RPM}= (1XN)= Machine $\text{speed}_{\text{mpm}}$ / πD_{roll}				

Table 2. Forming Roll Bearing frequencies.

Name	relative speed	bearing number	Roller no.	Cage Train Frequency (FTF)	Ball Spin Frequency (BSF)	Outer Race Frequency (BPFO)	Inner Race Frequency (BPFI)
Motor Non-drive side	1	SKF 6319	8	0.387	2.0992	3.096	4.904
Motor Drive Side	1	SKF 6319	8	0.387	2.0992	3.096	4.904
Gearbox High Speed	1	SKF 32313	16	0.4102	2.6268	6.5632	9.4368
Gearbox Low speed	0.25	SKF 32218	20	0.42	3.13	8.4	11.6
Forming Drive Side	0.25	SKF 23052	29	0.4552	5.54	13.2008	15.7992
Forming Non-Drive Side	0.25	SKF 23052	29	0.4552	5.54	13.2008	15.7992

Table 3. Comparison for Maintenance Strategies Cost based on risk consequence.

Maintenance Strategy Cost based on risk consequence	*Run to Failure* ***(RTF)***	*Preventive Maintenance* ***(PM)***	*Condition Based Maintenance* ***(CBM)***
Direct Maintenance cost/year "Labor + Material"	683.4$	3571.85$	739.97$
Downtime cost/year	8400$	2100$	420$
Cost of Possible damages/year	5000$	1250$	250$
Total Maintenance Annual cost ***(Percentage)***	14083.4$ (62%)	6921.85$ (32%)	1409.97$ (6%)