# A Combined Approach for Condition Monitoring of Steel Rollers using Vibration, Sound and Wear Particle Analysis

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## Abstract

This paper deals with a combined approach for condition monitoring the surface durability of cryogenically treated steel rollers using vibration sound and wear particle analysis in a Rolling Contact Fatigue (RCF) test rig. The vibration signals were analyzed using Fast Fourier Transform (FFT), Cepstrum and wavelet analysis for different test cycles. The vibration level and the sound pressure level at rolling contact frequency and its harmonics give a qualitative estimation of the wear and pitting occurring on the roller surfaces. The type of wear is found using periodic oil analysis.

## Introduction

Surface durability plays a vital role on the performance of gears, rolling bearings and cams and it is enhanced by surface treatment techniques. Surface durability is assessed in a rolling contact fatigue rig under various contact stress conditions. This assessment is a time consuming process. Hence, the surface condition monitoring techniques are used to eliminate the need for continuous attention of a person. The features extracted from the monitored signals are then correlated to various types of wear.

Earlier experience has shown that no single monitoring technique is capable of detecting all types of wear and accurately assesses the surface condition. Therefore, a combined approach of condition monitoring using vibration, sound and particle analysis may yield better result for surface durability studies as different transducers have exhibited good results individually in gear failure studies [1-4]. By performing Fast Fourier Transform (FFT) of the vibration signal and cepstrum analysis [4], it is possible to diagnose the surface deterioration and wear trends in the frequency spectrum. But these techniques provide an average frequency spectrum over the sampling period. Demarcation of time or location of the fault is not possible from the analysis. The time frequency wavelet analysis provides information regarding the location of the fault and the frequency levels [5-7]. Sound and vibration analysis still give a qualitative estimation of the wear that is taking place. By performing oil analysis at frequent intervals [8], and studying the morphology of the wear particles, the type of wear taking place can be predicted. These intervals can be fixed based on the vibration and sound studies. In this paper, a combined approach comprising vibration, sound and wear particle analysis to condition monitor surface integrity of cryogenically treated rollers is dealt in detail.

## Experimental procedure

The tests were conducted under controlled conditions in a nut-cracker type rolling contact fatigue test rig. Schematic diagram of the test rig is shown in Figure 1. The test rig is driven by a frequency controlled 5.5 kW 3 phase, 415 V AC induction motor through belt drive. The load is applied on the test specimen through support rollers by a hydraulic actuator that is capable of applying 50kN load. The load is measured using strain gauge based load cell connected to carrier frequency amplifier. The experiment is carried out under continuous lubricated condition using SAE 30 oil. The test roller is 20 id x 40 od x 12 mm wide. The support and loading rollers are 50 id x 95 od x 10 mm wide. Both surfaces were finished to 0.20$\mu$m Ra.

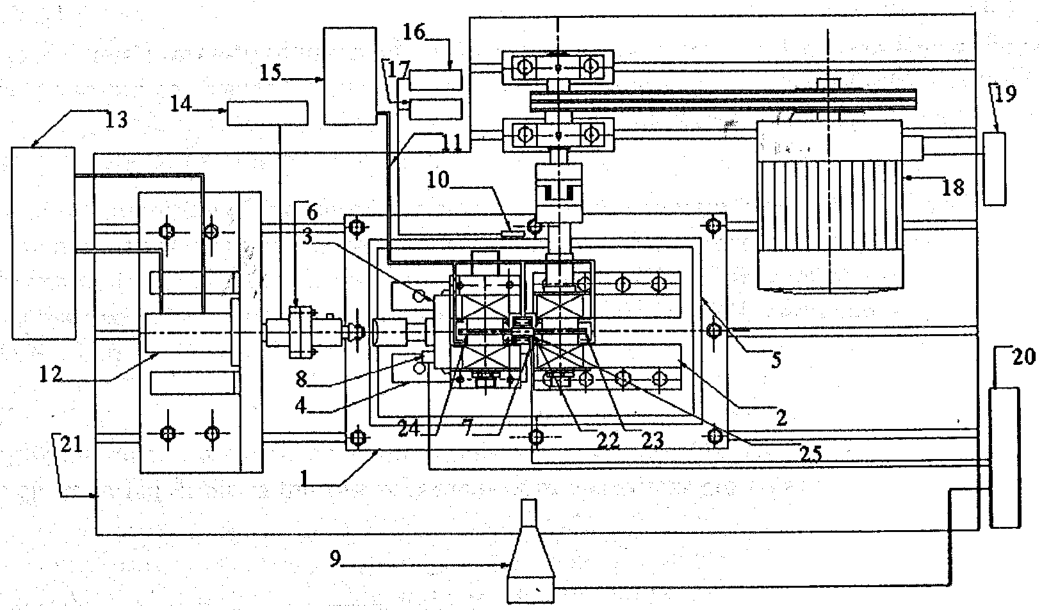
The vibration is measured using a piezoelectric accelerometer of sensitivity 100 mV/g with built in electronics to amplify the signal. It is mounted with a magnetic base on the loading plate in the direction of loading as shown in Fig.1. A proper cover is provided to shield it against splashing of oil. The accelerometer is powered by a 12 V DC source. The speed of the roller is measured using an optical sensor. The temperature of the roller and the bearings is continuously monitored using infra-red temperature probes of sensitivity 100mV/ºC. The sensors are powered by a 15 V DC source. The signals from the sensors are transmitted using shielded cables to input side of a 16 channel DAQ card. The 16-bit card has a sampling speed of 100ksamples/sec. It converts the analog signal into digital ones and stores in the computer.

The sound level is measured using B&K make sound level meter located 16 m above the floor level and 1m from the sound source (rollers). The instrument is provided with octave filters. The sound signals are acquired at regular intervals at 160Hz contact frequency and stored in the sound level meter. The stored data is transferred to the computer for further processing.

The online monitoring of the vibration signals in the time domain is done in the Lab-View environment. The offline analysis is done in MatLab environment. The data is processed for every 16 rotations of the roller. The sampling time is 0.12s. For the wavelet analysis, Time Synchronous Averaged (TSA) vibration signals of the test roller specimen are used. The algorithms for FFT, cepstrum and wavelet analysis are coded in MatLab environment.

**Results and Discussions**

The amplitude spectrum of the vibration signals taken for 16 rotations of the specimen roller at a load of 19kN is given in Fig.2. Since the test roller makes two contacts per rotation, its contact



1. Base Plate
2. Fixed housing block
3. Movable housing block
4. Linear motion slides for standard roller
5. Oil collection tray
6. Strain gauge based load cell
7. Infra red temperature sensor
8. Accelerometer
9. Sound level meter
10. Proximity pick up
11. Lubrication oil flowline
12. Hydraulic actuator 50kN capacity
13. Hyrdaulic power pack
14. MED amplifier with display
15. Lubrication unit
16. Speed display unit
17. Counter
18. 5.5 kwatt AC induction motor.
19. AC Frequency controller.
20. Data acquisition system.
21. Concrete bed
22. Roller specimen
23. Fixed standard roller
24. Movable standard roller
25. Linear motion slides for specimen roller

**Fig. 1 Schematic diagram of the RCF test rig with the instrumentation.**

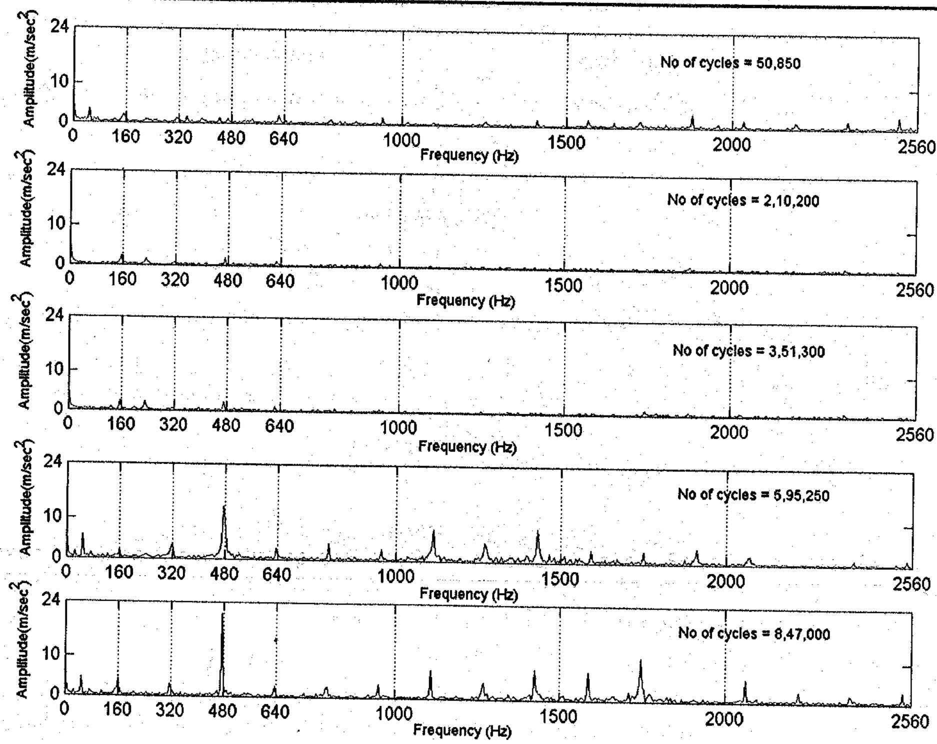



**Figure 2: Amplitude spectrum of the vibration signals at 19kN at different cycles**

frequency works out to 160Hz at its running speed of 4800rpm. The spectrum amplitude at contact frequency and its harmonics were found to rise with no of cycles. The amplitude spectrum is higher at the third harmonic compared to the other harmonics. Since this frequency was not associated with the bearings, it may be due to the higher wear occurring. The increase in spectrum amplitude is more towards the final failure stage (at 595,250) when the transition from mild wear to severe wear occurs. At higher cycles (above 595,250), there is an increase in the side bands around the meshing harmonics particularly at the third harmonic. The statistical analysis of the vibration signals showed that RMS and crest factor gives better diagnosis of the progressive wear compared to kurtosis and skewness. The statistical results are given in Fig.3.

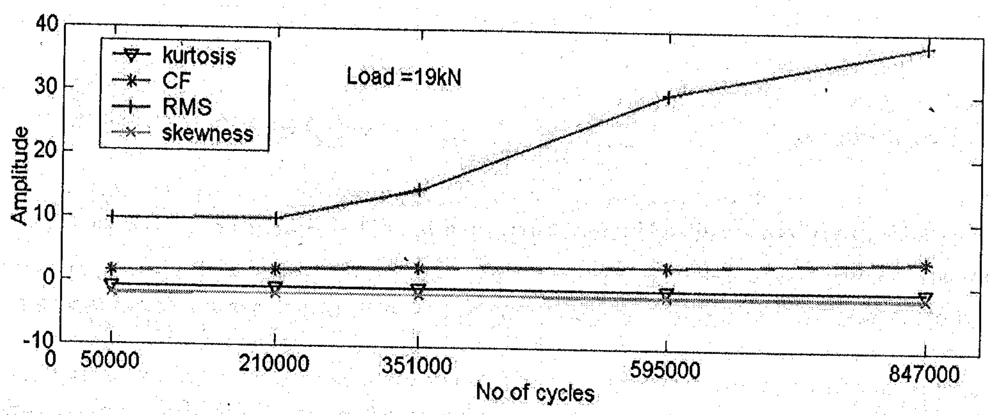



**Figure 3: The variation of statistical parameters of the vibration signal with no of cycles**

The cepstrum analysis of the vibration signals highlights the spectrum periodicity at 0.125 sec. It was found that the fault was getting repeated every 0.125 sec the time taken for one rotation of the specimen roller. The cepstrum analysis for vibration signals for load of 19kN at 50,000 cycles and 847,000 cycles is given in Fig.4. Although there is a slight increase in amplitude, cepstrum is almost insensitive to fault increment when compared to the FFT analysis.

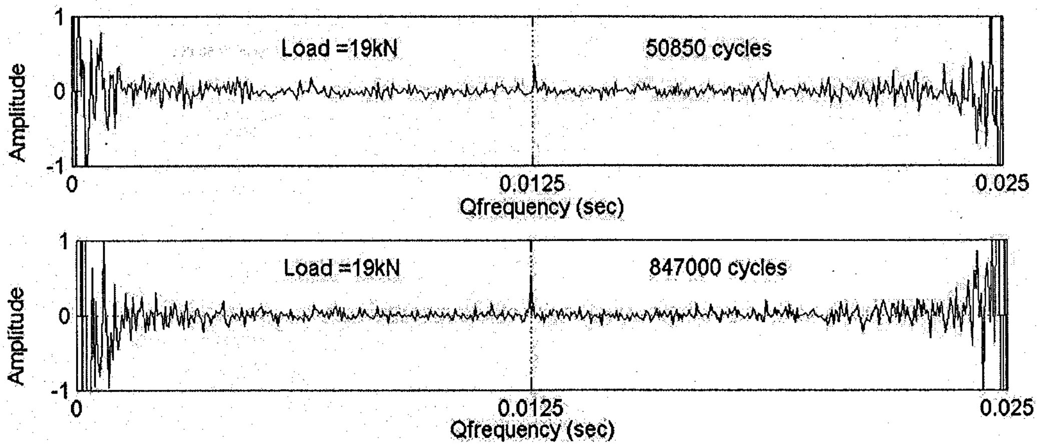



**Fig. 4. Cepstrum of the vibration signals for 19kN load at 50850 cycles and 847000 cycles.**

During the initial stages of the test, the wear is uniform and the variations or modifications in vibration signal is not significant to be detected by FFT analysis. Moreover, the signals are transient in nature. Hence, time frequency wavelet analysis was performed on the TSA signals to find the time evolution of the signals. TSA signals helps to avoid the effects of speed variations. The wavelet map for the initial (50,850) and final (847,000) cycles are shown in Fig.5. The wavelet map showed localized increase in wavelet amplitude at two regions for wide range of frequencies. These two regions correspond to the double contact of the fault for one rotation of the roller. The spread in the wavelet amplitude is more at final stages of the failure.

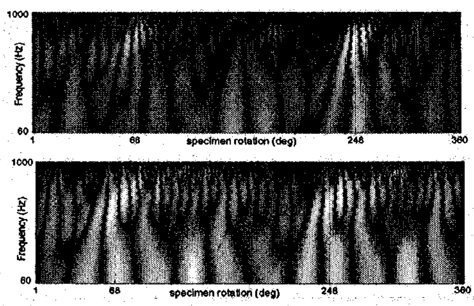



**Fig. 5: Wavelet plots for the TSA vibrat-ion signals for (a) 50850 & (b) 847000 cycles**

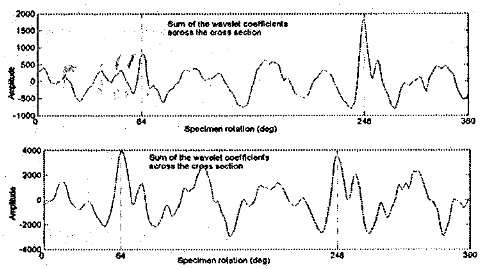



**Fig. 6: Wavelet Transform of TSA vibrat-ion signals at (a) 50,850 & (b) 847000 cycles**

The sum of the cross section of the wavelet plot was taken to get a better understanding of the localized fault. This shown in Figure 6: The localized increase in amplitude at 68$^0$ and 248$^0$ is shown in the wavelet plot for 400Hz frequency in Figure 7.

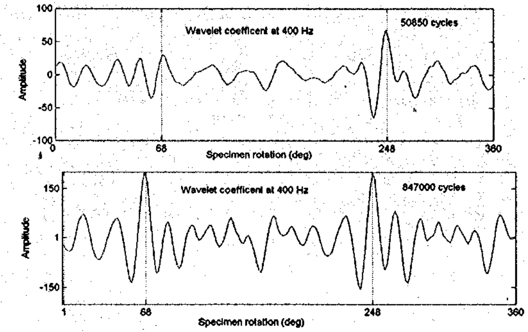



**Fig. 7: Wavelet transform of TSA vibration signals at 400Hz**

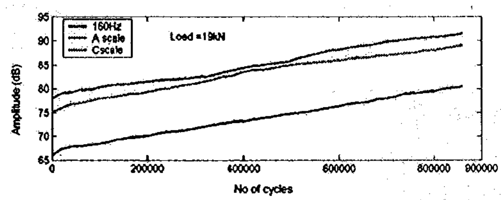
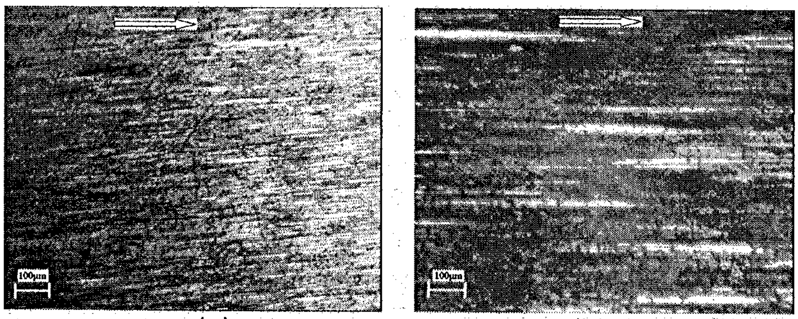



**Fig. 8: Variation in sound level with no of cycles at 19kN**

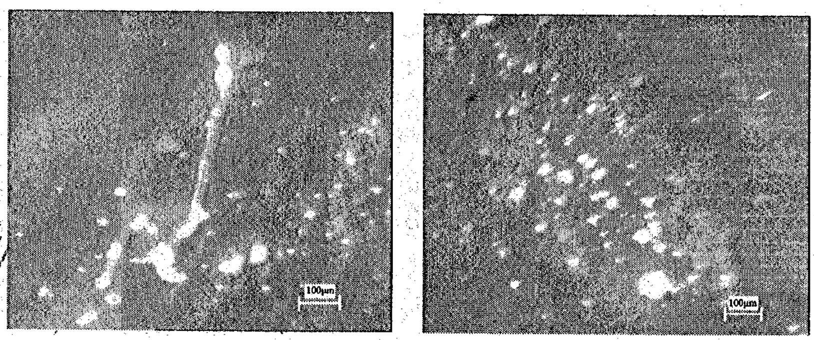
The sound level measured at A scale, C scale and 160Hz octave level is shown is shown in Figure 8. The sound level almost increases linearly with the number of cycles by 1 to 1.5 dB increase for every 100,000 cycles. At the failure 2 to 5 dB increase in sound level is seen. Although vibration and sound analysis helps in locating and providing surface deterioration trends, there is lack of information regarding the mode of wear that is taking place. The increased wear occurring can be seen from images of the wear tracks at 50,850 and 847,000 cycles shown in Figure 9. Wear article analysis was done for quantitatively estimation of the wear process.



(a) (b)

**Figure 9: The surface wear tracks at (a) 50,850cycles and (b) 847,000 cycles**

During the initial stages the size of the particle were less than 100 microns and were mainly cutting and laminar particles. But as the wear progressed size of the particles increased. At destructive pitting stage particles of 1000 to 2000 micorns were found. The oil analysis results are given in Table 1. The images of the particle distribution on the ferrograph slides are given in Figure 10:



(a) (b)

**Figure 10: (a) Images of Cutting particles on the slide at 210000 cycles (b) Particle distribution on slide at 351,000 cycles.**

The iron concentration in the oil samples using XRF and AAS is shown in Figure 11. The concentration levels increases drastically at 595000 cycles. This corresponds to the shift from mild wear to severe wear condition.

**Table 1: Details of the wear particle analysis**

| Wear debris analysis | 50000 | 210000 | 351000 | 595000 | 847000 |
|---|---|---|---|---|---|
| Particle size | < 50μm | < 100μm | < 200μm | < 250μm | < 500μm |
| Particle types | Cutting and laminar | Cutting and laminar | Cutting, laminar and fatigue particles | Cutting laminar and fatigue particles | Cutting laminar and fatigue particles |
| Surface roughness (Ra) | 0.20 | 0.25 | 0.33 | 0.43 | 0.62 |

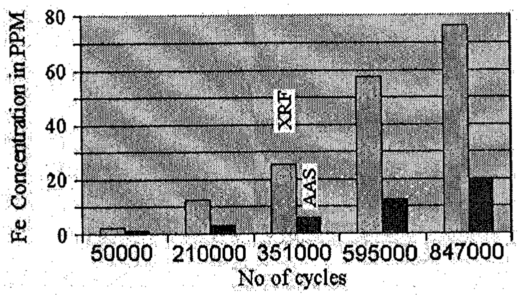



**Fig.11 Iron concentration in the oil samples at load of 19kN**

## Conclusion

The amplitude spectrum of the vibration data was found to increase at the contact frequency and its harmonics with the increase more pronounced at the third harmonic. The statistical analysis of the vibration data showed that RMS and crest factor are better parameters for diagnosing the wear compared to kurtosis and skewness. The cepstrum analysis revealed the periodicity in the vibration signal but failed to give information regarding incremental increase in wear. The wavelet analysis of the TSA signals gives better information regarding the location of the fault and the increment wear levels form the initial stages. The sound analysis also gives qualitative information about the progressive wear at A scale, C scale and 160Hz contact frequency. The oil analysis sampling was done based on the vibration and sound level The oil analysis gives quantitative information about the iron content and helps in demarking between mild wear and severe wear. An approach to monitoring the condition of the rollers based on vibration, sound and wear particle analysis is more beneficial.

## Reference


1. W Q Wang, F Ismail and F Golnaraghi, Assessment of gear damage monitoring techniques using vibration measurements,(2001), Mechanical systems and signal processing ,15(5), 905-922.
2. P D McFadden , Examination of a technique of failure in gears by signal processing of the time domain average of meshing vibration.(1987) Mechanical systems and signal processing 1(2) 173-183.
3. N Baydar and A Ball, Detection of gear failures via vibration and acoustic signals using wavelet transform. Mechanical systems and signal processing (2003) 12(4) 787-804.
4. R. B Randall , J HEE Breul and Kjaer Technical Review (1981) No 3, 3-40 Cepstrum analysis.
5. W.J Want, P.D McFadden, Application of wavelets to gearbox vibration signals for fault detection, J sound and vibration 192 (1996) 927-939.
6. W.J Staszewski, G.R Tomilson , Application of wavelet transform to fault detection in a spur gear. (1994), Mechanical systems and signal processing 8(3) 287-307.
7. A Yoshida, Y Ohue, H Ishikawa, Diagnosis of tooth surface failure by wavelet transform of dynamic characteristics, Tribology International 33 (2001) 273-279.
8. Z Peng, N Kessissoglou, An Integrated approach to fault diagnosis of machinery using wear debris and vibration analysis. Wear 255 (2003) 1221-1232.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