Summary Sheet

Reply to the Reviewers' Comments

Title of the Thesis: Signal Processing techniques on rotary optical encoder for fault detection in rotating machines

The author is profoundly grateful to the reviewers for their valuable suggestions, which have helped to improve the quality of the thesis significantly.

Response to Reviewer#1:

Q1. Page 10 Correct eqn. 2.1

The equation has been corrected and incorporated in the thesis. (Page-10)

Q2. Page 18 Correct eqn. 2.4 by including 1/2π in the expression on RHS

The equation *x(t)*= $\int_{-\infty}^{\infty} X(\Omega)e^{i\Omega t}\, d\Omega$to *x(t)*= $\frac{1}{2\pi}\int_{-\infty}^{\infty} X(\Omega)e^{i\Omega t}\, d\Omega$ (Page-18)

Q3. Page 22 Line 1: τ and ζ, not s

Necessary changes has been incorporated in the thesis. (Page-22)

Q4. Page 25 eqn. 2.23 should be corrected to modulus of log...on RHS.

$$C_x(n) = \frac{1}{2\pi}\int_{-\pi}^{\pi} log[X(\Omega)]\, e^{i\Omega n}\, d\Omega$$ is corrected by

$$C_x(n) = \frac{1}{2\pi}\int_{-\pi}^{\pi} log[|X(\Omega)|]\, e^{i\Omega n}\, d\Omega$$ (Page-25)

Q5. Page 35 Para 2 1st line is confusing.

In the area of condition monitoring, the vibration signal which is mostly used for condition monitoring, is generally captured from the machine casing. However, the rotational speed is directly measured from the output shaft of a machine and it is a direct response of changing dynamics. Therefore, structure borne noise attenuation in the IAS signal becomes less as compared to vibration signal. Due to this advantage, the varying rotational speed analysis has become an important technique in the area of condition monitoring. (Page-35)

Q6. Page 38 Notation used for time varying instantaneous phase is confusing

The varying instantaneous angular velocity $\omega_i + \delta\omega(t)$ changes to $\omega_0 + \delta\omega(t)$ instantaneous phase $\theta_s'(t)$ changes to $\theta_v(t)$. The new varying instantaneous angular velocity and phase is written as

$$\omega_v = \omega_0 + \delta\omega(t)$$

$$\theta_v(t) = \int_0^t [\omega_0 + \delta\omega(t)] N_s dt + \theta_i = N_s \omega_0 t + N_s \int_0^t \delta\omega(t) dt + \theta_i$$

Notation has been changed and incorporated in the thesis. (Page-38)

Q7. Pages 39, 40 and 41 Replace resister by register.

The necessary changes have been incorporated in the thesis. (Page-40, 42)

Q8. Page 39 Section 3.4.1 may be divided into two subsections to bring about greater clarity.

The section 3.4.1 is divided into another section. That section is added in the thesis named as **3.4.2 Measurable speed by Timer/ counter technique**.The corresponding change has been introduced everywhere. (Page-41)

Q9. Page 43 Zero crossing technique is also a time domain technique, Then why is (ii) alone called a time domain technique?

Yes, it is right. Here the convention is followed based on this paper (Gu et al., 2006).

Q10. Page 46 Define ω_v It is not given in the list of symbols.

This has been added in the list of symbols. (Page-xviii)

Q11. Page 49 Figure 3.6 Does the Figure show variation in output shaft rpm? If so this should be mentioned Giving input speed alone is not meaningful; give output speed or define gear ratios.

Yes, Figure 3.6, the IAS signal estimated from the pulse signal, which is shown in Figure 3.4(a). In Figure 3.5 the IAS signal also estimated similar pulse signal. The gear ratio is now defined in chapter 4 in page 44 and output speed will be 15.75 Hz has been mentioned in page 45.

(Page-45)

Q12. Page 50 Eqn. 3.24 Define A. Explain this eqn.

$$SNR = 3\left(\frac{\Delta f}{f_w}\right)^2 P_w \left(\frac{A^2/2}{P_n f_w}\right) \tag{3.24}$$

Where, P_w and P_n are power of varying part of the IAS and random noise respectively. Further Δf is a function encoder resolution (mentioned in equation no 3.22). f_w is highest frequency of time dependent variation $\delta\omega$ and A is amplitude of the FM signal. Therefore signal to noise ratio of estimated IAS can be improved by using encoder of higher resolution. (Page-50)

Q13. Page 51 Explain Fourier polynomial.

Fourier polynomials offers an approach of approximating general periodic functions by sums of very simple periodic sine and cosine functions, shifted and scaled.

Q14. Page 51 Eqn. 3.26 Why is summation over n/4 terms done? What is n?

The equation has been written by using 4 point rule (Yu et al., 2010). Therefore n has been replaced by $n/4$. Hence,$2n+1$ are total number of zero crossing points. The phase difference between two zero crossings is π/N_s radian. Considering $2\pi/N_s$ radian for Fourier series modelling, the effective number of zero crossings become n. (Page-52)

Q15. Page 52 Figure 3.8 shaft speed or gear ratio should have been given.

The output shaft speed of the gearbox has been introduced. The output shaft speed around 15.75 Hz, while input speed is 37 Hz. The detailed specification of the gearbox has been incorporated in chapter 4. (Page-68)

Q16. Page 56 Eqn. 3.33 Does * represents complex? if so mention.

* represents complex and it has been incorporated in the thesis. (Page-57)

Q17. Pages 57 to 60 Are the results in chapter 3 got using same gearbox as described in Chapter 4.

Yes, The results are presented in pages 57 to 60 in chapter 3 are actually got using same gearbox as described in Chapter 4. (Page-58, 60-61)

Q18. Pages 59 and 60 Why is IAS amplitude given in dB considering that it will not vary much? Refer Figure 3.11.

The amplitude around input, lay shaft, and output shaft frequencies are higher compared to gear mesh frequencies and higher frequencies. Therefore, the amplitudes in Y axis have been shown in dB scale. The Figure 3.11is showing comparative frequency spectra of IAS signal estimated from different IAS estimation techniques. Now all the figures have been changed and shown in RPM scale. (Page-60-61)

Q19. Page 65 Line 1 How is variability in input speed introduced.

The input speed varies by changing motor input frequency and voltage. (Page-65, 2^{nd} line)

Q20. Page 66 In eqns. 4.1, 4.2 and Fig. 4.4b, better explanation could have been given with consistent notations. Fig 4.4b could be made bigger. What are T_c and T_c^1? It would have been good to have a Table showing various shaft frequencies, gear ratios or number of teeth and gear meshing.

The Figure 4.4b) has been added as a sole and bigger Figure 4.5. The corresponding change has been introduced everywhere. (Page-66-68)

Figure 4.4: 4-speed Synchromesh gearbox.

Line diagram of gear meshing is shown in Figure 4.5. The detailed specification of the transmission gearbox and shaft frequencies are shown in Table 4.1 and 4.2, respectively. Number of teeth on input and lay shaft gear are 19 and 31, respectively. Moreover, the counter gear and main gear denoted by T_c and T, respectively. The prefix shown in Figure 4.5 is showing the corresponding gear operation.

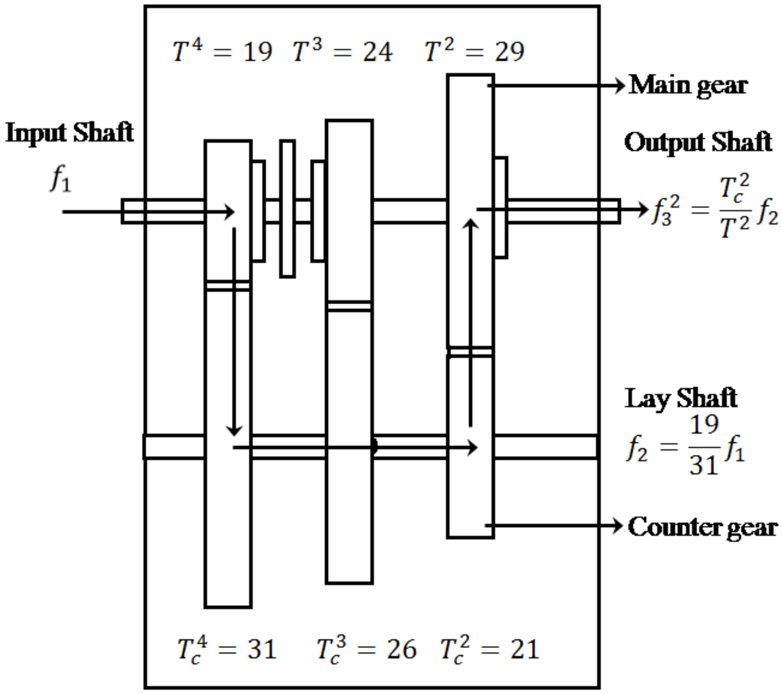

Figure 4.5: Line diagram of gear meshing.

Table 4.1: Specification of the gears

	2^{nd} Gear		3^{rd} Gear		4^{th} Gear	
	Main (T)	Counter (T_c)	Main (T)	Counter (T_c)	Main (T)	Counter (T_c)
No. of teeth	29	21	24	26	19	31
Pitch circle radius(x10-5 m)	3683	2667	3048	3302	2413	3937
Helix angle (^{0})	40	40	40	40	40	40
Pressure Angle (^{0})	14.5	14.5	14.5	14.5	14.5	14.5

Table 4.2: Specification of shaft frequency under different gear operations

Gear operation	No of teeth	Input shaft frequency	Lay shaft frequency	Output shaft frequency
2nd	Main=29 Counter=21	f_1	$f_2 = \frac{19}{31} f_1 = 0.6129 f_1$	$f_3^2 = \frac{19}{31} \times \frac{21}{29} f_1 = 0.4438 f_1$
3rd	Main=24 Counter=26	f_1	$f_2 = \frac{19}{31} f_1 = 0.6129 f_1$	$f_3^3 = \frac{19}{21} \times \frac{26}{24} f_1 = 0.6639 f_1$
4th	Main=19 Counter=31	f_1	$f_2 = \frac{19}{31} f_1 = 0.6129 f_1$	$f_3^4 = \frac{19}{31} \times \frac{31}{19} f_1 = f_1$

Q21. Page 69 Last line why are only three input speeds and 3 load conditions considered? It would have been good to take 4 or 5 of each to get better trends.

Yes, it would have been good. However, three input speeds and loads are sufficient.

Q22. Page 78 Figure 5.1 What is the nominal speed?

Input speed is 37 Hz. Due to slip, the induction motor runs at 35.5 Hz and output shaft frequency becomes 15.75 Hz. (Page-78)

Q23. Page 79 Figure 5.2 With more load conditions better trend would have been obtained.

During no load condition gears rotate freely. With load conditions, the load becomes an external source of vibration. Therefore, with more load conditions better trend would have been obtained.

Q24. Page 81 Figure 5.3 and page 82 Figure 5.4 What is the significance of $43f_3$ or $44f_3$? Normally we do not look at such harmonics. Where is the accelerometer mounted? I presume that high harmonics coincide with the casing of the gearbox; this can easily found out by doing impact test under non rotating condition. The casing resonance seems to be in the vicinity of 700 Hz. So any salient frequency component there get magnified. That is why fm4 is seen in Fig. 5.6, Page 86? This is also the reason for $41f_3$, $42f_3$, $43f_3$, $44f_3$, $41f_3$ etc. Which are seen in Figure 5.7 (Page 89), Figure 5.8 (Page 90) and Fig. 5.9 (Page 91). Also in Figs 5.11 and 5.12 is there a second resonance in the vicinity of 910 Hz causing $59f_3$, $60f_3$ etc.

The encoder is attached to the output shaft. The resonance could be the reason for $41f_3$, $42f_3$, $43f_3$, $44f_3$, $41f_3$ etc. The resonance of the casing is not measured.

In Figs 5.11 and 5.12, there is a second resonance in the vicinity of 910 Hz causing $59f_3$, $60f_3$ etc.

Q25. Chapter 5 It would have been good to see how effective your methods are for partial tooth removal?

Though it is not tested our method for partial tooth removal but in case of partial tooth removal, the IAS signal will show modulation characteristics. Hence, direct FFT, amplitude demodulation, cepstrum analysis will work for partial tooth removal. Moreover, the automated TSA will reduce the noise and will work for partial tooth removal.

Q26. Page 86 Second last line what is X_k. Is it V_k?

The necessary changes has been made in the thesis. (Page-86)

Q27. Page 92 Figure 5.10, Page 93 Figures 5.11-5.13 What amplitude have you plotted on Y axis?

Figure 5.11-5.13 show power spectra of frequency demodulated IAS signal. The unit of amplitude in Y axis is rad^2/s^2. It has been incorporated in each figure. (Page-93)

Q28. Page 95 Fig. 5.15 why are the signals are good with 2 teeth removed?

All the figures were not in a same scale. Now all the figures have been made in same scale.

(Page-95)

Q29. page 99 Figure 5.18, page 100 Figure 5.19 and page 101, Figure 5.20 amplitude in rotor vibration region of 0-100 Hz shows larger power spectra than in the 300 to 600 Hz range. Besides all figures shows higher power spectra in no load condition than under loaded condition. Why?

The Figures are showing power spectra of IAS signal measured from output shaft. Therefore, amplitudes around output shaft, lay shaft and input shaft frequencies are very high. This is the reason so that the amplitude in rotor vibration region of 0-100 Hz shows larger power spectra than in the 300 to 600 Hz range. The scale of power spectra at no load condition was not same with loaded condition. Therefore, the result was showing higher power spectra in no load condition than under loaded condition. Now it has been brought into same scale. (Page-99)

Q30. Page 102 Why has 3rd IMF have been chosen?

The selection of particular IMF has been done by calculating Maximum, minimum, and mean time period of each IMF. (Page-103)

Q31. Page 106 Figure 6.1 (a) and (b) pertaining to 2 different data sets have been shown.

Hence, the two signals are one is before time synchronous averaging and another one is after time synchronous averaging.

Q32. Page 107 Fig. 6.2 Higher harmonics of f_3 in the vicinity of 700 Hz are seen. Also on Page 108 Figure 6.3, Page 109 Figure 6.4, Page 110 Figure 6.5 and page 117 Fig 6.8, page 119 Fig 6.10 and page 124 Fig 6.15.

It could be reason of casing resonance.

Q33. Page 138 6th last line from bottom, Figure 7.8 should be corrected to 7.7.

The necessary changes have been made in Page 138 6th last line. (Page-138)

Q34. Page 139 Fig 7.7 Why has IMF6 been chosen?

The selection of particular IMF for time frequency domain analysis has been done by calculating minimum, mean, and maximum time period of each IMF. (Page-138)

Q35. Chapter 7 Page 142 Why RSM considered only for IC engine and not for gearbox? Why are other methods tried for gearbox not tried for IC engine?

The first motivation of this research was to detect the fault in multistage gearbox. Therefore, various statistical parameters have been compared in Figure 5.2. Moreover, the various method have been applied on gearbox's IAS signal to detect the gearbox fault. On the other side, the IAS signal from IC engine has been analysed by time domain, frequency domain and time frequency domain technique to detect Engine firing. Moreover RSM has been considered only to *understand the behaviour of IC engine. Amplitude demodulation, cepstrum analysis etc. are not applied as the motivation was to detect engine firing.*

Response to Reviewer #2:

Q1. Do you think that instantaneous angular speed could be used to identify a fault at the onset? If so, what steps would you take to make the procedure work?

Yes, The encoder pulse signal will be acquired online by data acquisition device and a program (zeros cross detection) will be incorporated with the device so that it can capture the pulse signal with duration of few revolutions. The instantaneous angular speed has to be estimated by zeros cross detection method. A low pass filter has to be applied to extract high frequency noise. Further, the IAS signal can be analysed by direct FFT, amplitude demodulation, cepstrum analysis to identify a fault at the onset.

Q2. What test would you recommend for testing the applicability of the procedure to detect a fault at the onset.

I would recommend Amplitude demodulation and cepstrum analysis for better onset fault detection. Furthermore, TSA with respect to lay shaft and output shaft would be done to increase the efficacy of fault detection process. However, automated time synchronous averaging cannot be applied during onset. As the technique is developed based on saved data. Hence, to accomplish TSA with respect to lay shaft another encoder or tachometer has to be included to the lay shaft.

Q3. State the steps that you would use to continuously monitor the structural health of a system using the approach described. How would you procure and then, more importantly, process the data?

i) Acquire the pulse signal online.

ii) Apply zeros cross detection technique to estimate IAS from pulse signal.

iii) Apply low pass filter to reduce high frequency noise.

iv) Apply direct FFT, amplitude demodulation, cepstrum analysis to continuously monitor the structural health of a system.

The thesis has been thoroughly grammar checked and few changes has been made on the thesis.

* Zero crossing technique has been changed into zeros cross detection technique.

Page no:11, 31, 32, 44, 51, 59, 61, 145, 154.

* Phase modelling by Fourier polynomial has been changed into zeros cross time modelling with Fourier series.

Page no: 11, 31, 44, 51, 52, 55, 59, 60, 61, 143, 144, 154.

* Complete ensemble empirical mode decomposition has been changed into Complementary ensemble empirical mode decomposition.

Page no: 101, 103, 104, 138.