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Maintenance Cost Optimization of Faulty Gearbox under Continuous Vibration Measurement Monitoring

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ABSTRACT:

Maintenance management for the gearbox systems aims at reducing the overall maintenance cost and improving the availability of the systems. Since the maintenance costs represent a substantial portion of the total life cycle costs, reliability and maintenance management of the gearbox systems have drawn increasing interests for the reduction of these costs. This paper considers a condition-based maintenance optimization for continuously degrading systems under continuous rotational vibration acceleration monitoring. After maintenance, the states of the system are randomly distributed with residual damage. An optimization technique is used to solve the preventive maintenance problem for faulty (cracked) gear tooth system. The situations where cracked gear tooth system has several ranges of performance levels are considered. To enhance cracked gear tooth system availability, possible preventive maintenance schedules are performed and affect strongly the effective age. Moreover, the technique is used to generate an optimal sequence of maintenance actions providing system working with the desired level of reliability during its lifetime with minimal maintenance cost rate. A single stage gearbox is used for this study, where multi-time tests were carried on healthy and faulty gearboxes individually. The measured and filtered rotational vibration acceleration was collected where hazard lifetime (LT) was determined at failure based on the Weibull distribution with assured reliability. The results indicate that the saving expected costs of either health or faulty gearbox, the basic maintenance cost (C), availability (AV) and maintenance basic cost & availability (CAV) savings have been estimated. On the other hand, the operating time between failure and optimum points for C, AV and CAV savings are all considered.

KEYWORDS:

Vibration response; Gearbox; Preventive maintenance; Weibull distribution; Condition monitoring; Hazard rate

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ACRONYMS & NOMENCLATURE:

$W_g(a; b)$	*Function after transformation*
$g^*(t)$	*Complex conjugation of g (t)*
a	*Scale parameter for dilation*
b	*Time translation*
$f(t)$	*Probability distribution function (time)*
$F(t)$	*Cumulative distribution function (time)*
$R(t)$	*Reliability function (time)*
$h(t)$	*Hazard value, or failure rate value, at time t*
η	*Characteristic life or is the scale parameter*
β	*Shape parameter*
C_p	*System preventive cost*
C_c	*System corrective cost*
$AV(T_p)$	*Availability*
t_p	*Preventive replacement down-time*
t_c	*Failure replacement down-time*
$C(T_p)$	*Maintenance cost function*
a_p	*Hourly preventive replacement cost per unit time*
a_c	*Hourly corrective replacement cost per unit time*

1. Introduction

Prognosis of gear life using the acoustic emission (AE) technique is relatively new in condition monitoring of rotating machinery. Experimental investigations on spur gears in which natural pitting was allowed to occur were described in [1-2]. Throughout the test period, AE, vibration and spectrometric oil samples were monitored continuously to correlate and compare these techniques to natural life degradation of the gears. It was observed that based on the analysis of root mean square (RMS) levels only the AE technique was more sensitive in detecting and monitoring pitting than either the vibration or spectrometric oil analysis (SOA) technique. It is concluded that as AE exhibited a direct relationship with pitting progression, it offers the opportunity for prognosis. Furthermore, the detection of both localized and distributed categories of defect has been considered.

Vibration measurement in both time and frequency domains along with signal processing techniques such as the high-frequency resonance technique have been covered. Other acoustic measurement techniques such as sound pressure, sound intensity and acoustic emission have been considered. Gearbox system reliability is a critical factor in the success of any industrial project. Poor reliability directly affects both the project's revenue stream through increased operation and maintenance costs and reduced availability to the system due to its down-time. Indirectly, the acceptance of the system by the financial and developer communities as a viable enterprise is influenced by the risk associated with the capital equipment reliability, increased risk, or at least the perception of increased risk, is generally accompanied by increased financing fees or interest rates. However, the reliability based on a developed analytical mathematical method for predicting remaining LT of cracked gear tooth was explored in [3].

The development was focused specifically on the investigation of a generalized statistical method for characterizing and predicting Weibull density function degradation (hazard rate). Using this method, optimal preventive age replacement policy was determined to maximize the gearbox system reliability, and consequently an optimal cost analysis can be estimated. A simple system was used as a medium for real data collection, where the torsional vibration acceleration or sound pressure levels was measured and analyzed. The results indicate that the knowing of the remaining LT and the optimized replacement cost of the faulty gear can enhance the process of scheduling maintenance, ordering spare parts and using resources, thereby consequently reduces the maintenance cost. The objective of condition based maintenance (CBM) is typically to determine an optimal maintenance policy to minimize the overall maintenance cost based on condition monitoring information.

The existing work reported in the literature only focuses on determining the optimal CBM policy for a single unit. In this paper, CBM of multi component systems, where economic dependency exists among different components subject to condition monitoring is investigated. The fixed preventive replacement cost, such as sending a maintenance team to the site, is incurred once a preventive replacement is performed on one component. As a result, it would be more economical to preventively replace multiple components at the same time. In this work, it is proposed a multi-component CBM system policy based on proportional hazards model (PHM). The cost evaluation of such a CBM policy becomes much more complex when we extend the PHM based CBM policy from a single unit to a multi-component system. A numerical algorithm is developed in this paper for the exact cost evaluation of the PHM based multi-component CBM policy. Examples using real-world condition monitoring data are provided to demonstrate the proposed methods [4-5]. The universal generating function (UGF) is combined with harmony search meta-heuristic optimization (HSO) method to solve a preventive maintenance (PM) problem for series-parallel system. The consideration of the situation where system and its components have several ranges of performance levels has been included. Such systems are called multi-state systems (MSS). The MSS measure was found to be related to the ability of the system to satisfy the demand. The development of an algorithm to generate an optimal sequence of maintenance actions providing system working with the desired level of reliability during its LT with minimal maintenance cost rate was considered. To evaluate the MSS system availability, a fast method based on UGF was suggested.

The harmony search approach can be applied as an optimization technique and adapted to this PM optimization problem. Moreover, the influence on the optimal periodic maintenance policy after considering the failure replacement in the last period of preventive maintenance (PM) was carried out. A partially periodic PM policy was proposed incorporating the costs of minimal repair, PM, failure replacement, and preventive replacement. The average cost rate for the proposed policy was obtained. Finally, the optimal parameters of the maintenance policy can be calculated using the cost rate function and the numerical comparisons of different policies are provided to demonstrate the effect of failure replacement [6-7]. The aforementioned review has shown that most of the earlier efforts were directed towards the consideration of the CBM optimization for continuously degrading systems under continuous rotational vibration acceleration monitoring applied on faulty (cracked) gear tooth system to reduce its maintenance effective cost.

Various authors have exposed their theoretical and experimental works; their contributions were limited. The available measuring equipment in experimental work was limited which makes the interpretation of the experimental results rather difficult. Moreover, the literature review has established that, there is a need for more theoretical and experimental investigations in this field. The purpose of this research is to investigate the influence on the optimal periodic maintenance policy after considering the failure replacement in the last period of PM. The situations where faulty (cracked) gear tooth system has several ranges of performance levels are considered. To enhance the cracked gear tooth system reliability during its LT with minimal maintenance cost rate, the possible preventive maintenance schedule actions are performed to the cracked gear tooth.

2. Continuous wavelet transform (CWT)

In non-stationary vibration waveform, the CWT concept is used. Wavelet transforms are inner products between signals and the wavelet family. These are derived from the mother wavelet by dilation and translation [8] as,

$$W_g = (a;b) = \frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty} x(t)\, g^*_{a,b}(t)\, dt \tag{1}$$

Where $W_g(a;\, b)$ is the function after transformed, and $g^*(t)$ stands for complex conjugation of g (t). If a daughter wavelet is viewed as a filter, wavelet transform is simply a filtering operation. Usually, reconstructing the wavelet coefficients at selected scales through certain methods attempted to be discovered. To do this, prior information had to be known on the signal needs to be identified. Morlet wavelet is one of the most popular non-orthogonal wavelets and is defined as,

$$\psi(t) = e^{-\frac{\beta^2 t^2}{2}} \cos(\pi t) \tag{2}$$

A daughter Morlet wavelet [9] is obtained by time translation and dilation from the mother wavelet as,

$$\psi_{a,b}(t) = \psi\left(\frac{t-b}{a}\right) = e^{-\frac{\beta^2 (t-b)^2}{2a^2}} \cos\left(\frac{\pi(t-b)}{a}\right) \tag{3}$$

Where a is the scale parameter for dilation and b is the time translation. It can also be looked at as a filter. To identify the immersed impulses by filtering, the location and the shape of the frequency band corresponding to the impulses must be determined first. Scale (a) and parameter β control the location and the shape of daughter Morlet wavelet respectively. As a result, an adaptive wavelet filter could be built by optimizing the two parameters of a daughter wavelet.

3. Hazard rate model

The maintenance cost depends on the probability distribution function (pdf). If the pdf is described mathematically by f(t), then the cumulative distribution function F(t) can be derived using [10]:

$$F(t)=\int_0^t f(t)\,dx \tag{4}$$

Whereas the sum of the reliability and the cumulative distribution function equal one then Eqn. (4) can be written as,

$$R(t)+F(t)=1 \tag{5}$$

Where *f(t)* is the probability distribution function (time), *F(t)* is the cumulative distribution function (time) and *R(t)* is the reliability function (time). The rate at which failures occur in a certain time interval [t, t+1] is called the failure rate during that interval as shown in Fig. 1.

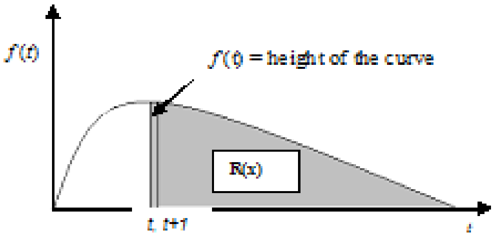

Fig. 1: Derivation of failure rate

Failure rate is defined as the probability that a failure per unit time occurs in the interval, given that a failure has not occurred prior to t, the beginning of the interval. Thus the failure rate (hazard rate) is obtained as,

$$h(t)=\frac{\int_t^{t+1} f(t)dt}{R(t)}=\frac{f(t)}{R(t)} \tag{6}$$

It will be seen that if dt = 1 and the height of the curve is assumed to be height *f(t)* between t and t+1. That means, when the decision maker obtains the pdf from the actual data for any system, he/she can derive the hazard function or the measured degradation of it. A prognostic system in terms of remaining LT output that only reported a specific time-to-failure without having any confidence bound associated with the prediction would be unwise. This is true for simple prognostic approaches that only utilize historical reliability data (such as Weibull distributions) to the more advanced prognostic modeling approaches that take design parameter and operating condition uncertainties into account. The data-driven prognostic modeling approach implemented in this paper takes advantage of the directly sensed parameter together with the historical reliability data to provide critical inputs for producing accurate failure predictions.

Information from rotational vibration acceleration (filtered) data measurements to represent gear's fault with high certainty are used. Based on Weibull distribution and the rotational vibration acceleration data measured for a healthy gearbox and faulty (cracked) gearbox at different operation conditions, the failure Weibull pdf is written as [11]:

$$f(t)=\frac{\beta(t)^{\beta-1}}{\eta^{\beta}}e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{7}$$

$$F(t)=1-e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{8}$$

From Eqns. (5) and (6), the hazard rate is given by,

$$h(t)=\frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \tag{9}$$

Where h(t) is the hazard value, or failure rate value, at time t, η is the characteristic life or is the scale parameter and β is the shape parameter.

4. Optimum maintenance policy for replacement

4.1. Age replacement cost model

The classical policy used in maintenance application is called age replacement (ARP). The principle of this maintenance strategy is to replace the component with a new one (i.e. maximal repair) when it fails or when it has been in operation for T_p time units, whichever comes first. The expected maintenance cost per unit time, C, can be written as [12]:

$$C(T_p)=\frac{C_pR(T_p)+C_cF(T_p)}{\int_0^{T_p} R(t)dt} \tag{10}$$

Where C_p is system preventive cost and C_c is system corrective cost.

4.2. Maintenance cost (C) minimization

The profit and loss statement of a company recognizes good performance as low production cost per unit. Therefore, a hazard level intervention point stated in previous sections that results in low cost has to be chosen. Intuitively, a policy resulting in very low hazard will be expensive has surmised. On the other hand, choosing to operate at a very high hazard will approach the cost of ignoring hazard and running to failure. It is concluded that there must be a best policy somewhere between the two extremes. To complete the CBM decision process, an additional relationship needs to be found. The relationship between hazard rate and significant operational (condition monitoring) data needs to be established to minimise the maintenance cost.

4.3. Availability (AV) model

Availability deals with the duration of up-time for operations and is a measure of how often the gearbox is functional. It is often expressed as (up-time) / (up-time + down-time) with many different variants. Availability also deals with at least 3 main factors [13-14]:

1) Increasing time to failure;

2) Decreasing down-time due to repairs or scheduled maintenance;
3) Accomplishing items 1 & 2 in a cost effective manner.

As availability grows, the capacity for making money increases because the component is in service for a larger percent of time. The parameters for the selection of an optimal predictive maintenance strategy are the fixed values for the down-times incurred by:

a) Preventive renewal (maintenance);
b) Renewal as a result of failure.

The costs of materials and labour are not considered as significant in this model. The AV model can be given as,

$$AV(T_p)=\frac{\int_0^{T_P} R(t)dt}{\int_0^{T_P} R(t)dt+t_pR(T_p)+t_cF(T_p)} \tag{11}$$

Where AV(T_p) is availability, t_p is preventive replacement down-time and t_c is failure replacement down-time. In this model, high availability was bought by paying for it with more frequent interventions. It is assumed that the cost of repair was negligible, and therefore can be ignored. The difference between failure and preventive repair times (rather than costs) dictated the exact nature of the compromise to achieve high component availability.

4.4. Combined maintenance cost and availability (CAV) model

The combined cost and availability optimization option is used to minimize the expected maintenance cost per unit time by taking into account of costs and duration of preventive and failure down-times, and cost of down-time. This cost model allows flexibility in setting up realistic parameters upon which to build the optimal decision model. For example, the fixed cost of failure replacement may be high (say due to the cost of a new part), but the down-time required may be short (just to replace the part). Alternatively, the cost of preventive work can be small, but the time to complete the work (down-time) can be long. This model resolves the extremely difficult problem of deciding upon maintenance policies in the light of actual maintenance costs. The expected maintenance cost and availability per unit time, CAV, can be calculated as [16],

$$CAV(T_p)=\frac{(C_p+a_pt_p)(1-Q)+(C_c+a_ct_c)Q}{W+t_p(1-Q)+t_cQ} \tag{12}$$

Considering the following, the CAV can be written as,

$$R(T_P)+F(T_c)=1,\quad R(T_P)=(1-Q),\quad F(T_c)=Q$$

$$W=\int_0^{T_P} R(t)dt$$

$$CAV(T_p)=\frac{(C_p+a_pt_p)R(T_p)+(C_c+a_ct_c)F(T_p)}{\int_0^{T_P} R(t)dt+t_pR(T_p)+t_cF(T_p)} \tag{13}$$

Where CAV(T_p) is the maintenance cost function and availability combined, a_p is hourly preventive replacement cost per unit time and a_c is hourly corrective (failure) replacement cost per unit time.

5. Experimental methodology

The experimental set-up used in this study is schematically shown in Fig. 2. It consists of 3-phase 5 HP AC motors and motor speed controller. A pair of spur gears is tested for fault state prognosis. The driving gear has 25 teeth and the driven gear has 64 teeth, with the module of 3 mm, pressure angle of 20° and face width of 7 mm. The gears used are off-the-shelf and thus, very representative of the most common precision applications. The motor speed controller allows tested gear operation in the range of 200 to 1400 rpm. The gearbox is powered by electric motor and consumes its power on a hydraulic disc brake. Rotational vibration acceleration is used to monitor the gearbox during operation. The system is sized to provide the maximum versatility to speed, load settings and use of different speed ratios other than listed in this paper. The motor, hydraulic disc brake, inverter and gearbox are hard-mounted and aligned on a bedplate. The bedplate is mounted using isolation feet to prevent the transmission of vibration to the floor. The shafts are connected with flexible and rigid couplings.

Fig. 2: Experimental set-up

Two Bruel & Kjaer accelerometers are mounted upon the gearbox case and are used to record the translational vibration acceleration signals, one in each side-axis with distance of 15 cm as shown in Fig. 3. The rotational vibration acceleration is calculated from the measured translation vibration accelerations. The sampling frequency used was 0.6 kHz and signals of 1 second were recorded. Bruel & Kjaer portable and multi-channel PULSE type 3560-B-X05 analyzer is used. The Bruel & Kjaer PULSE Labshop software type 7700 is used to analyse the results, see Fig. 4.

Fig. 3: Accelerometer positions

Fig. 4: Analysis instrumentation system

The speed is measured by a photo electric probe. Recordings were carried out at constant speed condition of 400 rpm. Representative tests on a gear system with a cut of root thickness to simulate the tooth crack were undertaken. Many tests were conducted on the same configuration yield similar parameters behaviour. A small crack of 3x0.2x40 mm, as shown in Fig. 5, was made artificially with wire electrical discharge machining at the root of pinion gear tooth to create a stress concentration which eventually led to a crack propagation. The translational vibration acceleration signals were taken, after allowing initial running of the gearbox for some time. Recordings for every 15 minutes were acquired and a total of 25 recordings (~ 360 minutes of test duration).

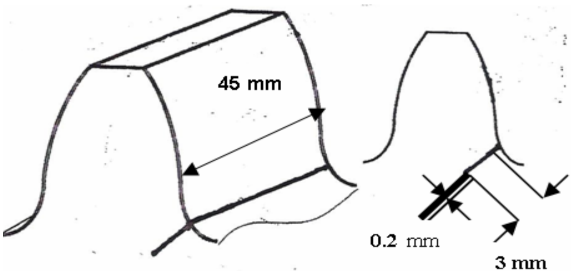

Fig. 5: Sketch of the gearbox tooth crack dimensions

6. Results and discussion

6.1. Failure LT determination

CBM data mainly provide information for short-term condition prediction only. Several data-driven prognostics models enabled gearbox prognosis using time series prediction. These models were simulated for single-step-ahead predictions to estimate the noise signal value. Two test cases (one healthy and one faulty gearbox) are considered to illustrate their hazard rates. Figs. 6 to 9 show the time history of rotational vibration acceleration responses in the form of measured signal and filtered signal for healthy and faulty gearboxes. Table 1 gives the RMS values of rotational vibration acceleration response in filtered signal form for healthy and faulty gearbox. Table 2 provides the values of the scale parameter and shape factor obtained from the interpretation of the results presented in Table 1. The hazard LT values of both healthy and faulty gearboxes were estimated from Eqn. (9) with the use of the shape factor and scale parameter values as presented in Table 2 based on Weibull distribution with assured reliability as shown Figs. 10 and 11.

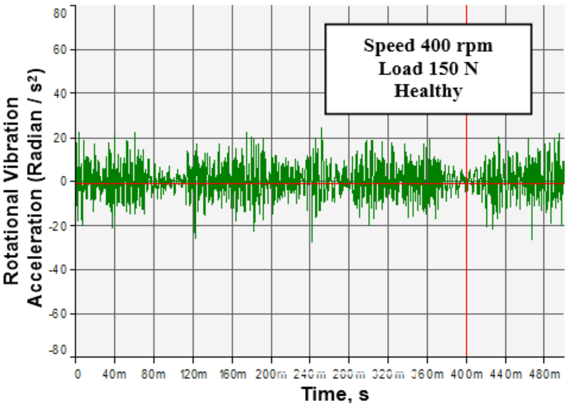

Fig. 6: Time history of vibration signal of healthy gearbox at testing time of 360 min (measured signal)

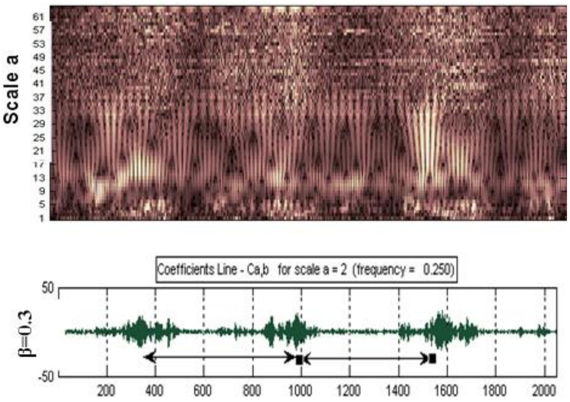

Fig. 7: Optimized wavelet analysis for healthy gearbox at testing time of 360 min (filtered signal)

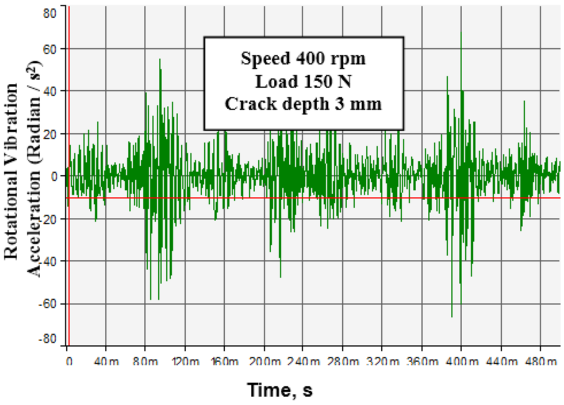

Fig. 8: Time history of vibration signal of faulty gearbox at testing time of 360 min (measured signal)

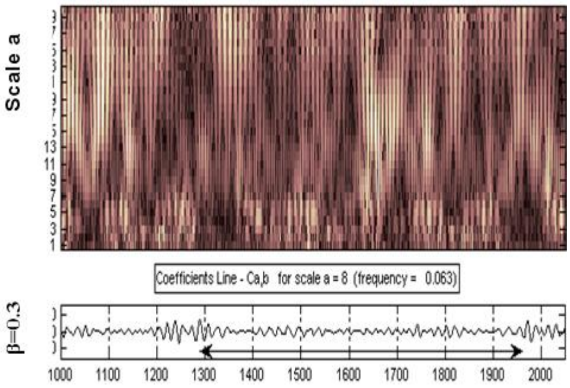

Fig. 9: Optimized wavelet analysis for faulty (cracked) gear box at testing time of 360 min (filtered signal)

Table 1: RMS of filtered rotational vibration acceleration at 3 mm crack depth, 400 rpm and 15 Nm torque load

Testing Time, min	RMS of filtered rotational vibration acceleration, rad/s^2	
	Healthy	Faulty (Cracked)
0	21.30	21.50
15	21.32	21.60
30	21.31	21.70
45	21.33	21.80
60	21.29	21.90
75	21.34	21.95
90	21.30	22.00
105	21.28	22.60
120	21.35	22.11
135	21.33	22.15
150	21.31	22.20
165	21.29	22.26
180	21.30	22.32
195	21.25	22.58
210	21.24	22.66
225	21.31	22.72
240	21.32	22.82
255	21.29	22.86
270	21.26	22.91
285	21.33	22.96
300	21.35	23.03
315	21.34	23.13
330	21.32	23.25
345	21.28	23.33
360	21.25	23.42

Table 2: Single number of scale parameter, shape factor and noise LT values at 400 rpm and 15 Nm torque load

Gearbox Condition	Shape Factor, β	η Value	LT Value
		minutes	
Healthy, New	3.5	8660	11000
Faulty, 3 mm crack depth	3.5	5500	6994

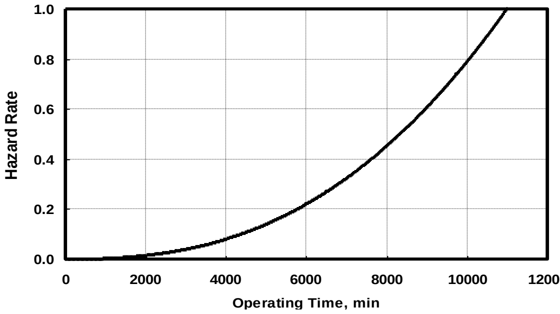

Fig. 10: Hazard LT at failure, healthy gearbox (3 mm) at 400 rpm and 15 Nm torque load

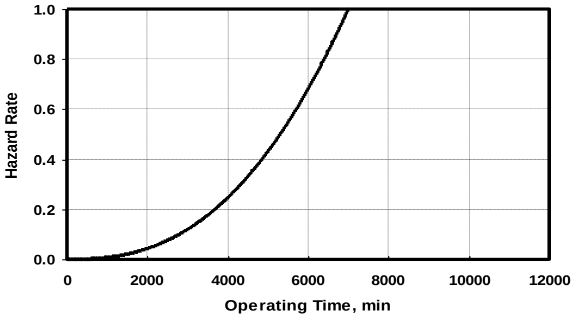

Fig. 11: Hazard LT at failure, faulty gearbox (3 mm crack depth) at 400 rpm and 15 Nm torque load

6.2. Maintenance cost estimation

The optimal decision policy is defined as the one that minimizes the average cost per unit working age of replacements (preventive and corrective maintenance). An estimation of the costs of corrective replacement and preventive replacement of 20000 L.E. and 4000 L.E. respectively are used in Ref. [4]. Alternatively, if maximum asset availability were the required optimization objective, one might apply a mean time to return to service. Two test cases (one healthy and one fault) are considered to illustrate their maintenance cost estimation. The basic maintenance cost for the healthy and faulty gearbox conditions in the range of hazard LT determined using Eqn. (11) are given in Table 3. In healthy gearbox, the basic maintenance cost (C) at failure point is 3.19 L.E./hr at 11000 min, while at the optimum point is 1.57 L.E./hr at 3654 min (see Fig. 11). However, the basic maintenance cost at failure of faulty gearbox is 5.02 L.E./hr at 6994 min, while at optimum point is 2.47 L.E./hr at 2317 min. The proposed models have successfully predicted the maintenance cost and availability for faulty gearbox.

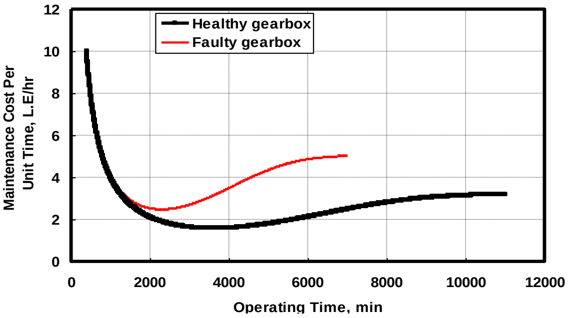

Fig. 11: Basic maintenance cost

Table 3: Results summary

a) Basic maintenance cost

Gearbox condition	Replacement policy	Basic maintenance cost	
		L.E./hr	Time hr
Healthy, New	Failure	3.19	11000
	Optimal	1.57	3654
	Saving,%	50.78	66.78
Faulty, 3mm crack depth	Failure	5.012	6994
	Optimal	2.47	2317
	Saving,%	50.79	66.87

b) Basic maintenance cost and availability

Gearbox Condition	Replacement policy	Availability		Basic maintenance cost & availability	
		Value	Time hr	L.E./hr	Time hr
Healthy, New	Failure	0.363	11000	1.192	11000
	Optimal	0.457	4427	0.7087	3212
	Saving,%	-25.89	59.75	40.45	70.80
Faulty, 3mm crack depth	Failure	0.363	6994	1.874	6994
	Optimal	0.457	2910	1.155	1980
	Saving,%	-25.89	58.92	38.37	71.69

The achieved availability may include the time of maintenance & replacement corrective and preventive actions. In order to develop a realistic maintenance policy, the effectiveness of the maintenance policy by calculating the availability of the system is assessed. The availability of healthy and faulty gearbox conditions in the range of hazard LT determined based on Eqn. (9) is shown in Fig. 12. In the basic maintenance cost model, replacement is bought at lower cost with frequent intervention. The time-to-repair was neglected. The difference between failure and optimum maintenance costs has dictated the exact nature of the compromise to impact the minimum production cost per unit. The difference between failure and preventive repair times (rather than costs) has dictated the exact nature of the compromise to achieve high gearbox component availability in the range of component hazard LT. The time for the gearbox component either healthy or faulty to reach the threshold after maintenance actions and before replacement may be decreasing due to aging; more frequent maintenance actions and longer maintenance times are required to keep the gearbox as functional.

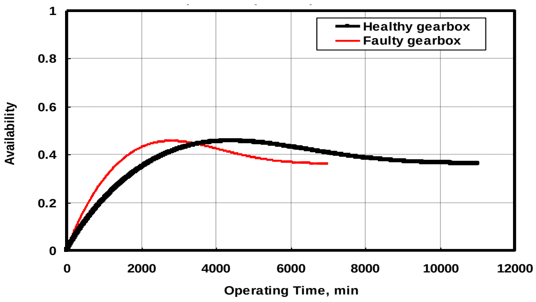

Fig. 12: Achieved availability

The healthy and faulty gearbox conditions in the range of hazard LT determined based on Eqn. (10) is shown in Fig. 13. Fig. 14 shows comparison between the maintenance cost with and without availability, where the cost without availability is lower than that for the cost with availability. Figs. 15 and 16 show the preventive and corrective cost results for the healthy and faulty gearboxes in the range of hazard LT respectively, and are tabulated in Table 4. The preventive and corrective cost data are determined based on Eqn. (8) after divided into two parts related to Cp (preventive) and Cc (corrective). For healthy gearbox, the percentage of preventive cost from the total basic cost at optimum point is 64.58%, while for the corrective cost is 35.42%. For faulty gearbox, the percentage of preventive cost from the total basic cost at optimum point is 63.56%, while for the corrective cost is 36.44. Both preventive and corrective costs for faulty gearbox are lower than those determined for healthy one. The preventive and corrective costs are equal at the intersection point..

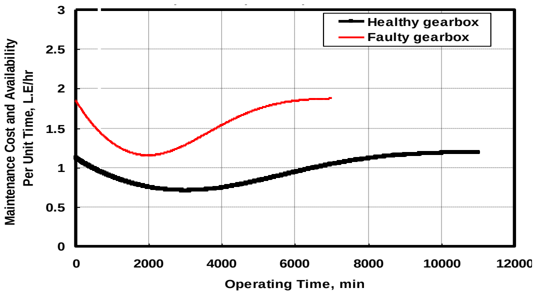

Fig. 13: Maintenance cost & availability – Healthy gearbox

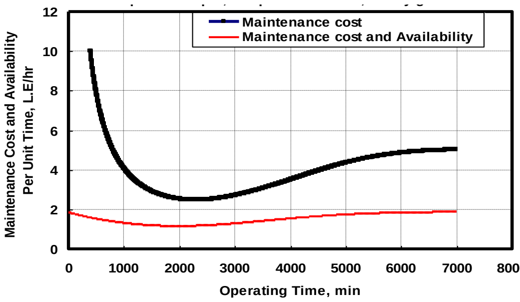

Fig. 14: Maintenance cost & availability - Faulty gearbox

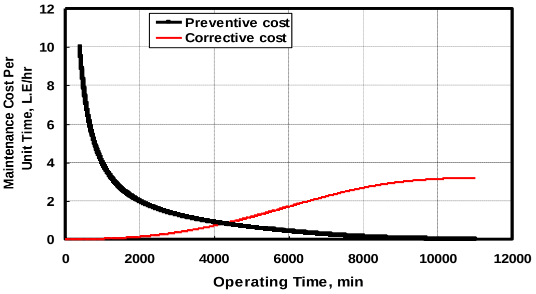

Fig. 15: Healthy gearbox, the preventive and corrective cost results

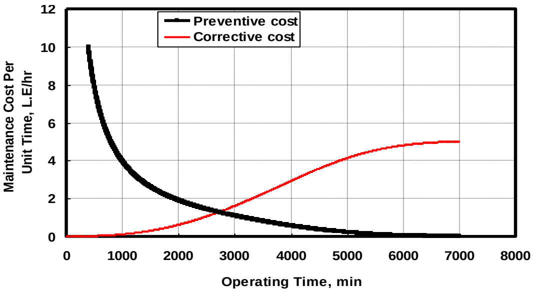

Fig. 16: Faulty gearbox, the preventive and corrective cost results

Table 4: Preventive & corrective costs for RMS filtered rotational vibration acceleration, (-) refers to value increase

a) Preventive cost

Gearbox condition	Replacement policy	Total cost L.E./hr	Basic maintenance cost, preventive Value L.E./hr	Time Hr	%
Healthy-New	Failure	3.185	0.0	11000	0.0
	Optimal	1.57	1.014	3654	64.58
	Saving	1.62	-1.014	7.346	-62.59
Inter. point	Cost = 50.78L.E./hr		Time = 4507 min		
Faulty, 3mm crack depth	Failure	5.012	0.0	6994	0.0
	Optimal	2.47	1.57	2317	63.56
	Saving	2.55	-1.57	4677	-61.57
Inter. point	Cost = 1.902L.E./hr		Time = 3251 min		

b) Corrective cost

Gearbox condition	Replacement policy	Total cost L.E./hr	Basic maintenance cost, corrective Value L.E./hr	Time Hr	%
Healthy-New	Failure	3.185	3.185	11000	100
	Optimal	1.57	0.557	3654	35.42
	Saving	1.62	2.628	7346	162.5
Inter. point	Cost = 50.78 L.E./hr		Time = 4507min		
Faulty, 3mm crack depth	Failure	5.012	5.012	6994	100
	Optimal	2.47	0.901	2317	36.44
	Saving	2.55	4.111	4677	161.5
Inter. point	Cost = 1.902 L.E./hr		Time = 3251min		

In maintenance cost and availability, Figs. 17 and 18 show the preventive and corrective cost and availability results for the healthy and faulty gearboxes in the range of hazard LT respectively and is tabulated in Table 5. The preventive and corrective cost and availability data are determined based on Eqn. (13) after divided into two parts related to Cp and Cc. For healthy gearbox, the percentage of preventive cost and availability from the total basic cost and availability at failure point is 0.0, while for the corrective is 100. For healthy gearbox, the percentage of preventive cost and availability from the total cost and availability at optimum point is 73.33, while for the corrective cost and availability is 26.67. For faulty gearbox, the percentage of preventive cost and availability from the total cost and availability at optimum point is 76.41, while for the corrective cost and availability is 23.59. Figs. 19 and 20 depict the variation of preventive and corrective cost with respect to healthy and faulty gearbox respectively, where the variation of preventive cost is nearly the same for either healthy or faulty gearbox, while the variation of corrective cost is higher for faulty gearbox with shorter operating time than that for healthy gearbox.

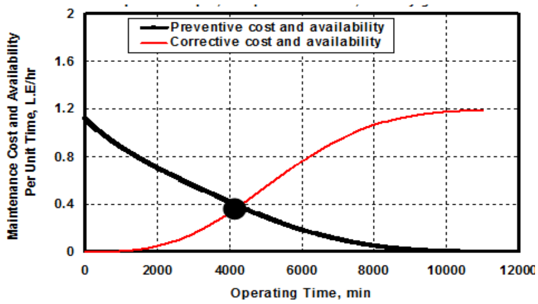

Fig. 17: Healthy gearbox - Preventive and corrective cost and availability results

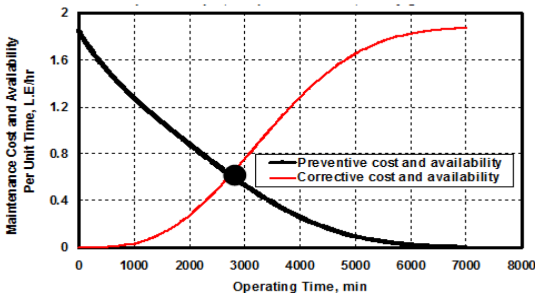

Fig. 18: Faulty gearbox - Preventive and corrective cost and availability results

Table 5: Preventive & corrective costs and availability for RMS filtered rot. vibration acceleration, (-) refers to value increase

a) Preventive cost and availability

Gearbox condition	Replacement policy	Total cost L.E./hr	Maintenance cost and availability, preventive		
			Value L.E./hr	Time Hr	%
Healthy-New	Failure	1.192	0.0	11000	0.0
	Optimal	0.709	0.520	3212	73.3
	Saving	0.483	-0.52	7.788	-108
Inter. point	Cost = 0.420 L.E./hr		Time = 4443 min		
Faulty, 3mm crack depth	Failure	1.874	0.0	6994	0.0
	Optimal	1.155	0.887	1980	76.4
	Saving	0.719	-0.88	5.004	-122
Inter. point	Cost = 0.625 L.E./hr		Time = 2762 min		

b) Corrective cost and availability

Gearbox condition	Replacement policy	Total cost L.E./hr	Maintenance cost and availability, corrective		
			Value L.E./hr	Time Hr	%
Healthy-new	Failure	1.192	1.189	11000	100
	Optimal	0.709	0.185	3212	26.67
	Saving	0.483	1.004	7.788	7.7
Inter. point	Cost = 0.420 L.E./hr		Time = 4443min		
Faulty, 3mm crack depth	Failure	1.874	1.872	6994	100
	Optimal	1.155	0.261	1980	23.59
	Saving	0.719	1.611	5.004	22.40
Inter. point	Cost = 0.625 L.E./hr		Time = 2762min		

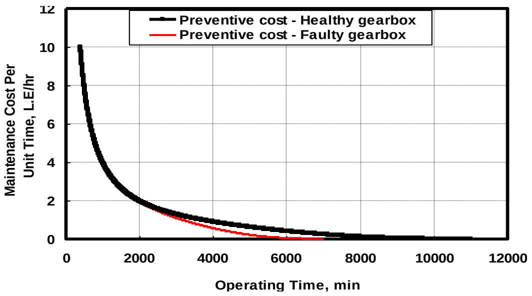

Fig. 19: Preventive cost and availability results for healthy and faulty gearboxes

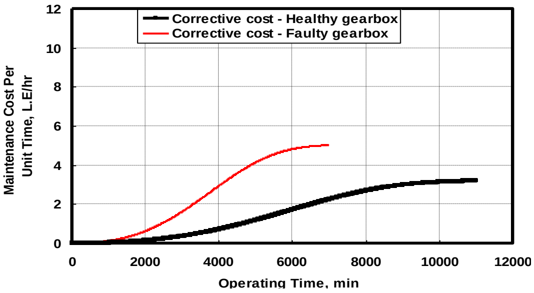

Fig. 20: Corrective cost and availability results for healthy and faulty gearboxes

7. Conclusions

Condition monitoring of rotating machinery and power drive trains is of utmost importance in various industrial applications. A single-stage gearbox was utilized in order to study the cost analysis of damage in artificially induced crack in the gear tooth using cost analysis models. Multi-min tests were conducted and numerous recordings were acquired using filtered rotational vibration acceleration responses monitoring. The technique described herein can be used as a practical way to improve the return on investment in their existing CBM systems. The following conclusions are drawn:

1. The determination of the basic cost analysis for gear tooth crack based on the RMS filtered rotational vibration acceleration responses, where all the basic maintenance cost results converge to the optimal value of the age replacement policy which has the same configuration when inspection interval increases.
2. The cost saving associated with early detection of incipient failures are quantified. This will require better tracking of costs associated with various types of repairs.

3. High availability has been bought by paying for it with more frequent intervention. The basic cost of maintenance was neglected. The operating time between failure and optimum for basic cost, availability and maintenance cost savings are all better.

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