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Condition Based Maintenance Optimization for Faulty Gearbox under Continuous Noise Monitoring

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Authors' contributions

This work was carried out in collaboration between all authors. Author SMM designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Author SAA managed the analyses of the study and the literature searches. All authors read and approved the final manuscript.

Research Article

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ABSTRACT

This paper considers a condition-based maintenance optimization for continuously degrading systems under continuous noise response in terms of sound pressure level monitoring. After maintenance, the states of the system are randomly distributed with residual damage. An optimization technique is used to solve a preventive maintenance problem for cracked gear tooth system. In this work, the situations where cracked gear tooth system has several ranges of performance levels are considered. To enhance cracked gear tooth system availability or (reliability), possible schedule preventive maintenance actions 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 availability or (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 sound pressure levels were 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 cost, availability; and maintenance cost and availability savings have been estimated. On the other hand, the operating time between failure and optimum points for basic cost, availability and maintenance cost and availability savings are all considered.

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Keywords: Optimization; replacement; availability limit; preventive maintenance policy; deteriorating component; weibull distribution; noise; hazard rate.

1. INTRODUCTION

The condition monitoring of a lab-scale, single stage, gearbox using different non-destructive inspection methodologies and the processing of the acquired waveforms with advanced signal processing techniques is present in [1-2]. Acoustic emission (AE) and vibration measurements were utilized for this purpose. The experimental setup and the instrumentation of each monitoring methodology were presented in detail. Emphasis was given on the signal processing of the acquired vibration and acoustic emission signals in order to extract conventional as well as novel parameters features of potential diagnostic value from the monitored waveforms. Innovative wavelet-based parameters features were proposed utilizing the discrete wavelet transform. The evolution of selected parameters/features versus test time was provided, evaluated and the parameters with the most interesting diagnostic behavior were highlighted. The differences in the parameters evolution of each NDT technique were discussed and the superiority of AE over vibration recordings for the early diagnosis of natural wear in gear systems was concluded. Moreover, an experimental investigation that assesses the effectiveness of AE in identifying seeded defects on helical gears; the first known attempt. Additionally vibration analysis has also performed to study the effect of seeded defect on the vibration signature of the meshing gears.

The vibration signal measured from a bearing contains vital information for the prognostic and health assessment purposes. However, when bearings are installed as part of a complex mechanical system, the measured signal is often heavily clouded by various noises due to the compounded effect of interferences of other machine elements and background noises present in the measuring device. It is stated that reliable condition monitoring would not be possible without proper de-noising. This was particularly true for incipient bearing faults with very weak signature signals. A new de-noising scheme was proposed in this paper to enhance the vibration signals acquired from faulty bearings. The Gabor wavelet was used in the wavelet transform and its parameters, i.e., scale and shape factor were selected in separate steps. The proper scale was found based on a novel resonance estimation algorithm. The algorithm makes use of the information derived from the variable shaft rotational speed though such variation was highly undesirable in fault detection since it complicates the process substantially. The shape factor value was then selected by minimizing a smoothness index. The index was defined as the ratio of the geometric mean to the arithmetic mean of the wavelet coefficient moduli. De-noising results were presented for simulated signals and experimental data acquired from both normal and faulty bearings with defective outer race, inner race, and rolling element [3].

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 [4-5]. Throughout the test period, AE, vibration and spectrometric oil samples were monitored continuously in order 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. An explanation for the vibration and noise generation in bearings was given. 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 (O&M) costs and reduced availability to the system due to its downtime. 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 an analytical mathematical method for predicting remaining lifetime of cracked gear tooth has been explored in [6-7]. The development was focused specifically on the investigation of a generalized statistical method for characterizing and predicting system Weibull density function degradation (hazard rate). Using this method, optimal preventive age replacement policy was determined to maximize gearbox system reliability, and consequently an optimal cost analysis can be estimated. A simple geared 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 lifetime and the optimized replacement cost of the faulty gear can enhance the process of scheduling maintenance, order spare parts and using resources; consequently reduce 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, we investigate CBM of multi component systems, where economic dependency exists among different components subject to condition monitoring. 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 system CBM 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 [8-9].

The universal generating function (UGF) is combined with harmony search (HSO) meta-heuristic optimization 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). To enhance system availability or (reliability), possible schedule preventive maintenance actions are performed to equipments and affect strongly the effective age. 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 availability or (reliability) during its lifetime 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 [10-11].

However, 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 preventive maintenance (PM). The situations where cracked gear tooth system and its components have several ranges of performance levels are considered. To enhance cracked gear tooth system availability or (reliability) during its lifetime with minimal maintenance cost rate, the possible schedule preventive maintenance actions are performed to the cracked gear tooth and affect strongly the effective age.

2. EXPERIMENTAL METHODOLOGY

The experimental set-up used in this study is schematically shown in Fig. 1, while Fig. 2 shows the instrumentation system. 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 64 teeth, with the module of 3.0 mm, pressure angle 20º and 7.0 mm face width. The gears used are off-the-shelf and thus, very representative of the most common and average 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. One non-destructive technique has been employed to monitor the gearbox during operation, namely noise measurement. Measurements of noise is in terms of sound pressure levels (SPLs). Bruel & Kjaer (B&K) portable and multi-channel PULSE type 3560-B-X05 with condenser ½ in- microphone and preamplifier type 4189A-021. The B&K PULSE labshop is the measurement software type 7700 is used to analyse the results (Fig. 2). Recordings were carried out at constant speed of 400 rpm. The sampling frequency used was 1.6 kHz and signals of 1s duration were recorded. In terms of various parameters evolution during the test - from a representative test on a gear system with a cut of root thickness to simulate the tooth crack will be presented and detailed in this study. Many tests were conducted on the same configuration yield similar parameters behavior. A small crack 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 propagating crack. The crack is done at tooth root with dimensions of 3.0 x 0.2 x 40 mm and is shown in Fig. 3. The size of cracks is a little bigger than one can encounter in the practical situation. The SPL signal from was taken, after allowing initial running of the gearbox for sometime. Recordings every 15.0 min were acquired and a total of 25 recordings (~ 360.0 min of test duration) and one in healthy condition were resulted until the termination of the test.

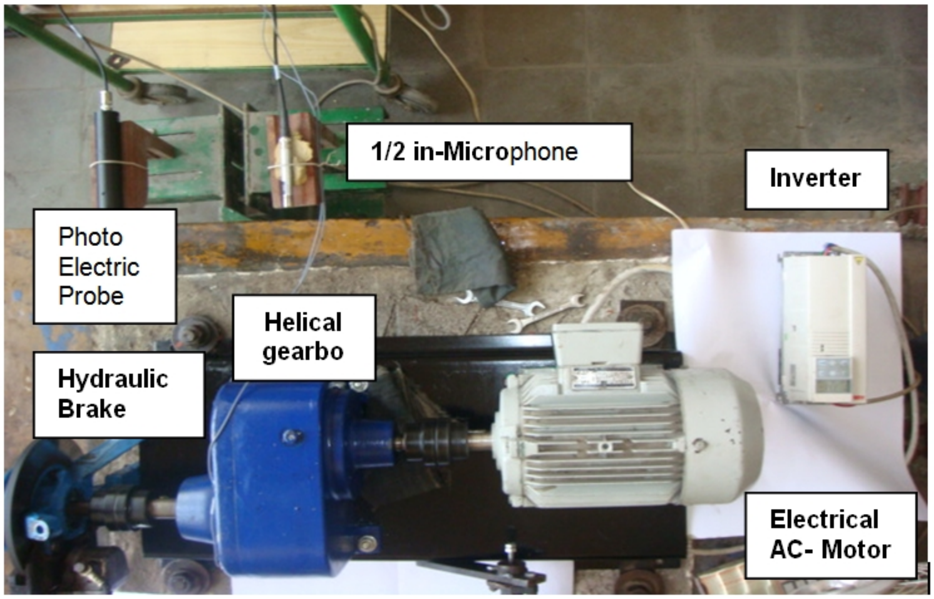

Fig. 1. The experimental set-up

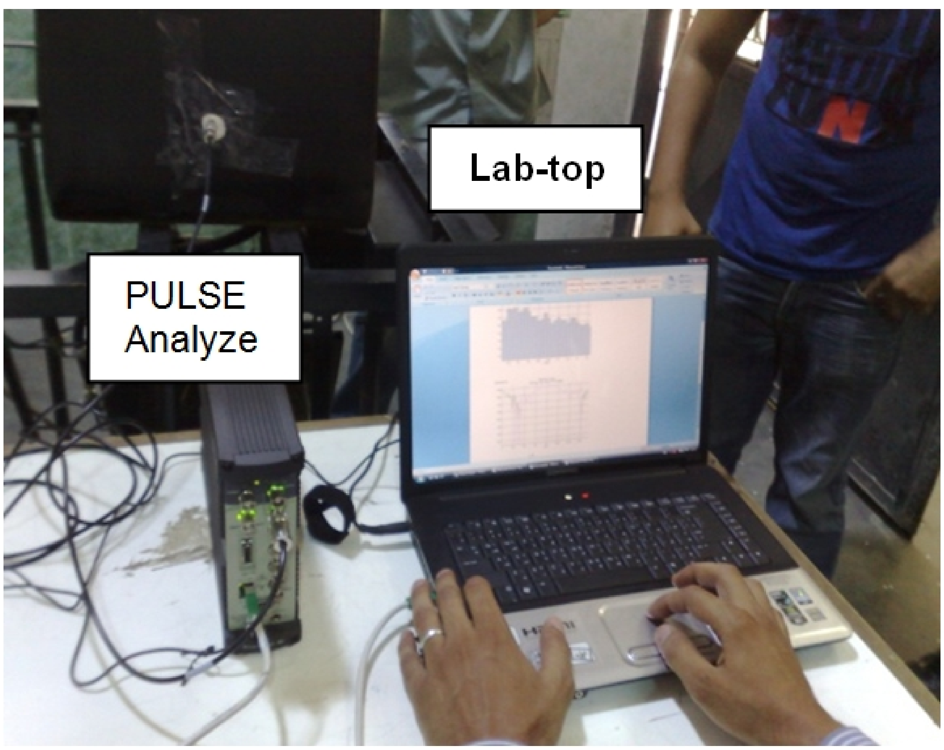

Fig. 2. Analysis instrumentation system

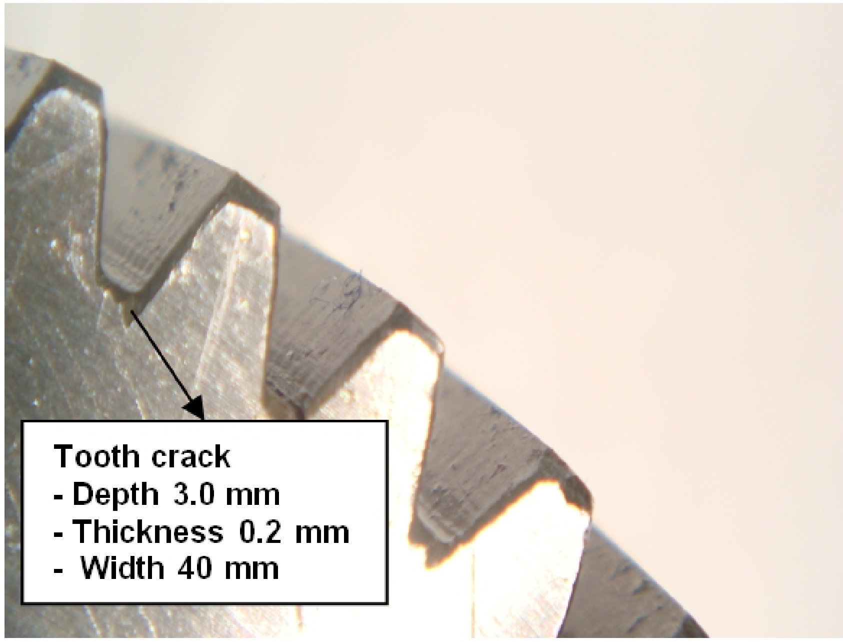

Fig. 3. Gearbox gear tooth crack

3. HAZARD RATE MODEL

The maintenance cost depends on the probability distribution function (pdf), if the probability distribution function is described mathematically by f(t), then the cumulative distribution function F(t) can drive by continuous integration as the following [12]:

$$F(t) = \int_0^t f(t)dx. \tag{1}$$

Whereas the sum of the reliability and the cumulative distribution function equal one then the equation can be written as

$$R(t) + F(t) = 1 \tag{2}$$

where

f(t) : is the probability distribution function (time).
F(t) : is the cumulative distribution function (time).
R(t) : is the reliability function (time).

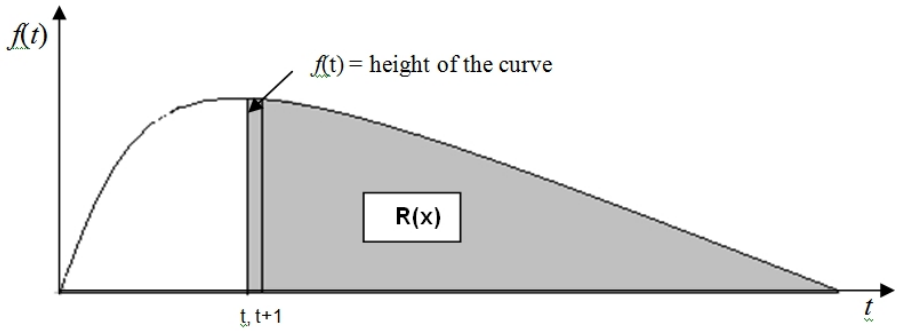

Fig. 4. Derivation of failure rate

The rate at which failures occur in a certain time interval [t, t+1] is called the failure rate during that interval (Fig. 4). It 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

$$h(t) = \frac{\int_{t}^{t+1} f(t)dx}{R(t)} = \frac{f(t)}{R(t)} \tag{3}$$

$$\int_{t}^{t+1} f(t)dt = f(t)$$

It will be seen that if dt is equal to 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 probability distribution function from the actual data for any system, he can derive the hazard function or the measured degradation of it. On the other hand, after knowing the measured degradation of the system, the remaining useful lifetime of it can be predicted.

A prognostic system in terms of remaining lifetime 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 data measurements to represent gear's fault with high certainty are used.

Based on Weibull distribution and the sound pressure level (SPL) data measured for a healthy gearbox and faulty gearbox at different operation conditions, the failure Weibull probability density function is written as following [12]:

$$f(t) = \frac{\beta (t)^{\beta-1}}{\eta^{\beta}} \exp[-(\tfrac{t}{\eta})^{\beta}] \tag{4}$$

From equation. (1), then

$$F(t) = 1 - \exp[-(\tfrac{t}{\eta})^{\beta}] \quad (5)$$

From equations (2) and (3), the hazard rate given by

$$h(t) = \frac{\beta}{\eta}(\frac{t}{\eta})^{\beta - 1} \quad (6)$$

where

h (t) : is the hazard value, or failure rate value, at time t.
η : is the characteristic life or is the scale parameter.
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 failure replacement policy, or age replacement (ARP). Under a preventive maintenance policy, the replacement of the component is either made after a specified time interval or in the case of component failure before the next scheduled time for replacement. The idea of this maintenance strategy is to replace the component with a new one (i.e. maximal repair) when it fail or when it has been in operation for T_o time units, whichever comes first. The expected maintenance cost per unit time, C, can be written as [13]:

$$C(T_p) = \frac{C_p R(T_P) + C_c F(T_p)}{\int_0^{T_P} R(t)dt} \quad (7)$$

Where

C_p: is system preventive cost.
C_c: is system corrective cost.

4.2 Maintenance Cost Minimization

The profit and loss statement of a company recognizes good performance as low, per unit, production cost. Therefore, a hazard level intervention point states 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 some where between the two extremes. To complete the CBM decision process an additional relationship needs to be find. The relationship between hazard rate and significant operational (condition monitoring) data needs to be established.

4.3 Availability Model

Availability deals with the duration of up-time for operations and is a measure of how often the gearbox is alive and well. It is often expressed as (up-time) / (up-time + downtime) with many different variants. Up-time and downtime refer to dichotomized conditions. Up-time refers to a capability to perform the task and downtime refers to not being able to perform the task, i.e., uptime = not downtime. Availability issues also deal with at least three main factors [14-15]: 1) increasing time to failure, 2) decreasing downtime due to repairs or scheduled maintenance, and 3) accomplishing items 1 and 2 in a cost effective manner. As availability grows, the capacity for making money increases because the component is in service a larger percent of time.

A maximum availability model is one of the three options for the selection of an optimal predictive maintenance strategy. The parameters of this strategy must to be considered. They are fixed values for the downtimes incurred by:

1. Preventive renewal (maintenance), and
2. Renewal as a result of failure.

The costs of materials and labor are not considered significant in this model, or they are believed to be proportional to downtime and, thus, can be ignored.

$$AV(T_p) = \frac{\int_0^{T_P} R(t)dt}{\int_0^{T_P} R(t)dt + t_p R(T_P) + t_c F(T_p)} \tag{8}$$

where:
$AV\,(T_p)$: is availability.
t_p : is preventive replacement downtime.
t_c : is failure replacement downtime.

In a symmetrical way, the maximum availability model focuses completely on downtime. In this report, high availability had bought by paying for it with more frequent intervention. It is assumed that the cost of repair was negligeable, or was proportional to the cost, and therefore could 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 Maintenance Cost and Availability Combined Model

The combined cost and availability optimization option is used to minimize expected maintenance cost per unit time taking into account costs and duration of preventive and failure downtimes, and cost of downtime. This cost model allows for flexibility in setting up realistic parameters upon which to build the optimal decision model. For example

1. The fixed cost of failure replacement may be high (say due to the cost of a new part), but
2. The downtime required may be short (just to replace the part).

Or, by comparison, the situation may be that:

1. The cost of preventive work can be small, but
2. The time to complete the work (downtime) 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, *C + AV*, can be calculated presented in [16]:

$$C(T_p) + AV(T_p) = \frac{(C_p + a_p t_p)(1-Q) + (C_c + a_c t_c)Q}{W + t_p(1-Q) + t_c Q} \tag{9}$$

Putting:

R(Tp)+ F(Tc)=1
R(Tp) = (1-Q)
F(Tc) = Q

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

Then *C + AV* can be written as

$$C(T_p) + AV(T_p) = \frac{(C_p + a_p t_p)R(T_P) + (C_c + a_c t_c)F(T_p)}{\int_0^{T_P} R(t)dt + t_p R(T_P) + t_c F(T_p)} \tag{10}$$

where:

$C(T_p) + AV(T_p)$: is maintenance cost function and availability combined.
a_p : is hourly preventive replacement cost per unit time.
a_c : is hourly corrective (failure) replacement cost per unit time.

5. RESULTS AND DISCUSSION

5.1 Failure Lifetime Determination

Individual operating vehicle gearbox components do not replace reliability data that reflect population characteristics. CM data mainly provide information for short-term condition prediction only. Several data-driven prognostics models enabled gearbox prognosis using time series prediction. These models mainly performed single-step-ahead predictions to estimate the noise signal feature value. Two test cases (one healthy and one faulty) are considered to illustrate their hazard rates. Figs. 5 and 6 show the time-domain history and overall level of noise in terms of sound pressure levels (SPL) in the form of measured signal at speed of 400 rpm and torque load of 15 Nm for healthy gearbox respectively, while Figs. 7 and 8 show the same for faulty gearbox (tooth crack) respectively. Table 1 collects the overall levels values of sound pressure level (P_a) at testing time from 0.0 to 360 min with increment of 15 min, from which the relationship between the overall SPL and testing time can be obtained for the Faulty gearbox and is shown in Fig. 9. The overall level of noise in terms of SPL is used in equation (6), where the hazard lifetimes (LT) are estimated based on the Weibull distribution with assured reliability change with the change gearbox conditions. The lifetime at failure is obtained when the hazard rate in Fig. 10 is equal to 1.0. The values of the scale parameter and shape factor for faulty gearbox are obtained from the interpretation of the overall SPL results in Table 1, while for healthy gearbox are taken from Grant et al. [17]. Table 2 tabulates the values of the scale parameter and shape factor for both healthy and faulty gearboxes along with the values of failure lifetime values.

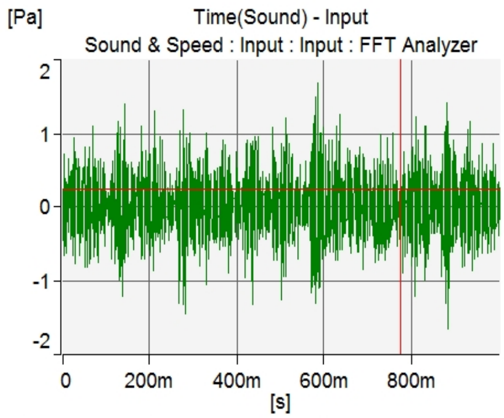

Fig. 5. Time history of sound pressure signal of healthy gearbox

Speed 400 rpm, Torque load 15 Nm

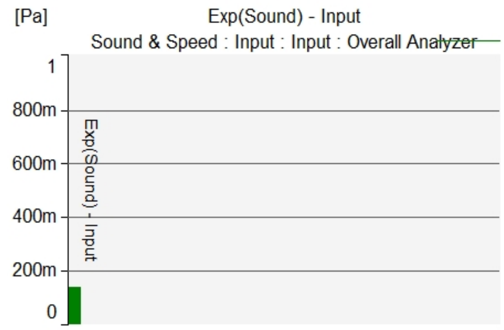

Fig. 6. Overall level of sound pressure signal of healthy gearbox

Speed 400 rpm, Torque load 15 Nm

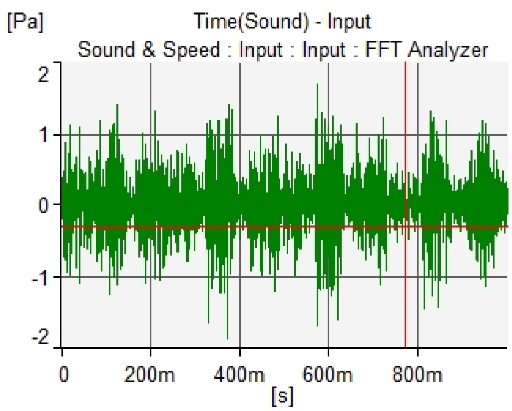

Fig. 7 Time history of sound pressure signal of faulty gearbox at testing time of 360 min

Speed 400 rpm, Torque load 15 Nm

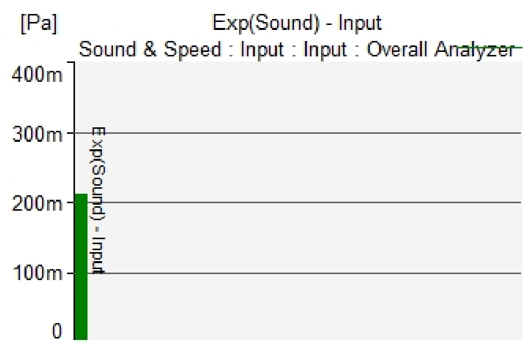

Fig. 8 Overall level of sound pressure signal of faulty gearbox at testing time of 360 min

Speed 400 rpm, Torque load 15 Nm

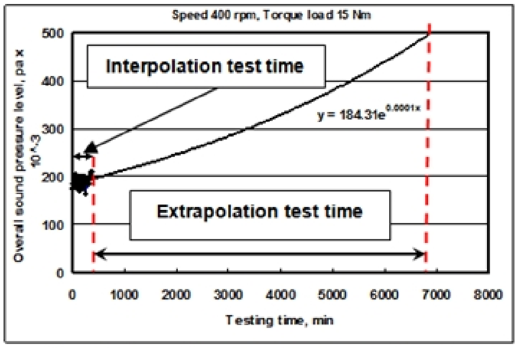

Fig. 9. Overall sound pressure level vs. testing time, Faulty gearbox

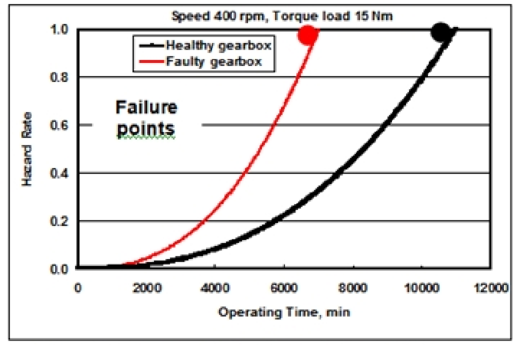

Fig. 10. Hazard lifetime (LT) at failure

Table 1. Overall sound pressure level (OSPL) at crack depth 3.0 mm, speed 400 rpm, torque load 15 Nm

Testing time, min	Healthy	0.0	15	30	45	60
overall sound pressure level, P_a x 10^{-3}	170	175	185	190	200	203

75	90	105	120	135	150	165	180	195	210
195	180	175	190	170	200	185	190	200	175

225	240	255	270	285	300	315	330	345	360
200	185	165	190	195	190	185	200	205	210

Table 2 .Single number of the scale parameter, shape factor and noise signal lifetime (LT) values

No.	**Gearbox condition**	**Speed, rpm**	**Torque load. Nm**	**Shape factor, β**	**η Value min**	**LT value**
1	Healthy, New	400	15	3.5	8660	11000
2	Faulty, Crack depth 3.0mm	400	15	3.5	5500	6994

LT: Lifetime; η : is the characteristic life or is the scale parameter

5.2 Maintenance Cost Estimation

5.2.1 The optimal decision policy

The optimal decision policy is defined as 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 [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.

5.2.2 Basic maintenance cost

Basic maintenance cost of the healthy and faulty gearbox conditions in the range of hazard lifetime (LT) determined based on equation (8) and tabulated in Table 3. In healthy gearbox, Fig. 11 shows the values of the basic maintenance cost data at failure point is 3.19 L.E./hr at 11000 min, while the values at optimum point is 1.57 L.E./hr at 3654 min. Moreover, the values of the basic maintenance cost data at failure of faulty gearbox is 5.02 L.E./hr at 6994 min, while the values at optimum point is 2.47 L.E./hr at 2317 min. It can be seen, precisely, the results of applying the optimal CBM policy. In Table 3, the saving expected results in the case of healthy gearbox, the basic maintenance cost (L.E./hr) saving 50.78%. On the other hand, the operating time between failure and optimum (hr) saving is 66.78%. In the case of the faulty gearbox, the maintenance cost (L.E./hr) saving is 50.79%. On the other hand, the operating time between failure and optimum (hr) saving is 66.87%.

5.2.3 The achieved availability

The achieved availability may include the time of corrective maintenance, corrective replacement, preventive maintenance and preventive replacement. 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 lifetime (LT) determined based on equation (9) and tabulated in Table 3, and shown in Fig. 12 which illustrates the values of the availability data at failure and optimum points. In the basic maintenance cost model, it is bought lower cost by paying for it with more frequent intervention. It is assumed that the time -to- repair was neglected, or was proportional to the cost, and therefore could be ignored. The difference between failure and optimum maintenance costs dictated the exact nature of the compromise in other that overall impact on the per unit production cost be minimum. In the symmetrical way, the maximum availability model focuses completely on downtime. In Fig. 12, high availability has been bought by paying for it with more frequent intervention. It is assumed that the basic cost of maintenance was neglected, or was proportional to the repair time and therefore could be ignored. The difference between failure and preventive repair times (rather than costs) dictated the exact nature of the compromise to achieve high gearbox component availability in the range of component hazard lifetime (LT) presented in Table 3. It is indicated that in the case of healthy gearbox, where the data shown in Fig. 12 which estimated the values of the availability data at failure point is 0.363 at 11000 min, while the values at optimum point is 0.363 at 4427 min. In the case of the faulty gearbox the values of the availability data at failure point is 0.363 at 6994 min, while the values at optimum point is 0.457 at 2910 min. It has been seen that 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 operating. In other words, the average short-run availability of the system will be decreasing since the expected uptime decreases whereas the expected downtime increases. It can be seen, precisely, the results of applying the optimal CBM policy. In Table 3, the saving expected results in the case of healthy gearbox, the availability saving is -25.89%. On the other hand, the operating time between failure and optimum (hr) saving is 59.75%. In the case of the faulty gearbox, the availability saving is -25.89%. On the other hand, the operating time between failure and optimum (hr) saving is 58.92%.

5.2.4 Maintenance cost and availability

Maintenance cost and availability of the healthy and faulty gearbox conditions in the range of hazard lifetime (LT) determined based on equation (10) and tabulated in Table 3. In healthy gearbox, Fig. 13 shows the values of the maintenance cost and availability data at failure point is 1.192L.E./hr at 11000 min, while the values at optimum point is 0.7087 L.E./hr at 3212 min. Moreover, the values of the basic maintenance cost and availability data at failure of faulty gearbox is 1.874 L.E./hr at 6994 min, while the values at optimum point is 1.155 L.E./hr at 1980 min. It can be seen, precisely, the results of applying the optimal CBM policy. In Table 3, the saving expected results in the case of healthy gearbox, the maintenance cost and availability (L.E./hr) saving is 40.45%. On the other hand, the operating time between failure and optimum (hr) saving is 70.80%. In the case of the faulty gearbox, the maintenance cost and availability (L.E./hr) saving is 38.37%. On the other hand, the operating time between failure and optimum (hr) saving is 71.69%. 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.

Table 3.Summarized maintenance cost, availability, and maintenance cost and availability for overall sound pressure level (OSPL)

No.	Gearbox condition	Replacement policy	Speed 400 rpm, torque load 15 Nm					
			maintenance basic cost		availability		Maintenance cost and availability	
			Value L.E./hr	Time hr	Value	Time hr	Value L.E./hr	Time hr
1	Healthy, New	At Failure	3.19	11000	0.363	11000	1.192	11000
		Optimal	1.57	3654	0.457	4427	0.7087	3212
		Saving	1.62	7346	-0.094	6573	0.4833	7788
		Saving,%	50.78	66.78	-25.89	59.75	40.45	70.80
2	Faulty, Crack depth 3.0mm	At Failure	5.012	6994	0.363	6994	1.874	6994
		Optimal	2.47	2317	0.457	2910	1.155	1980
		Saving	2.55	4677	-0.094	4084	0.719	5014
		Saving,%	50.79	66.87	-25.89	58.92	38.37	71.69

(-) refers to value increase

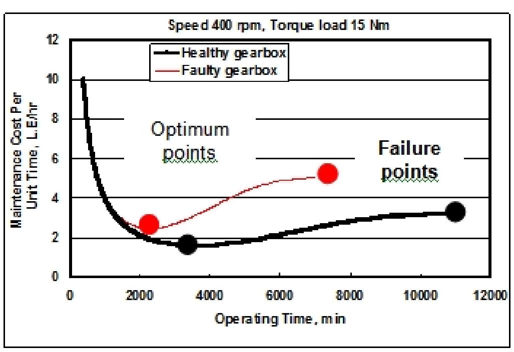

Fig. 11. Basic maintenance cost,

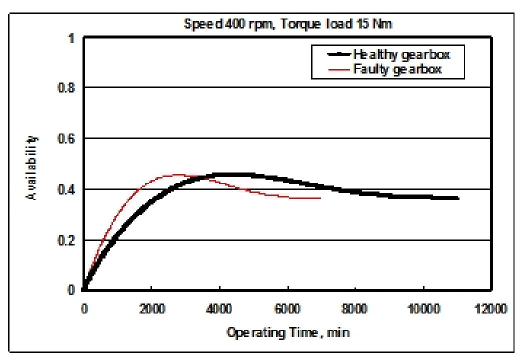

Fig. 12. The achieved availability

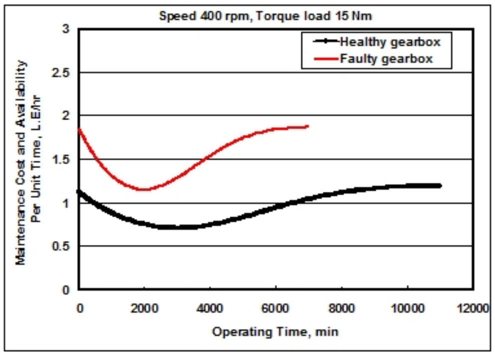

Fig. 13. Maintenance cost and availability

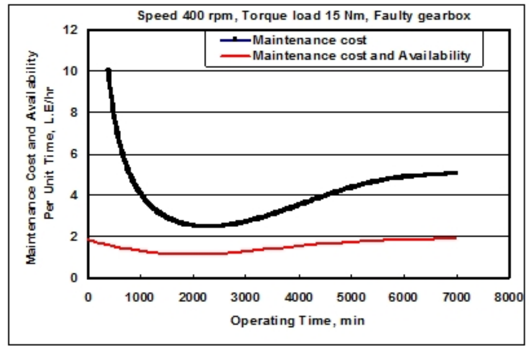

Fig. 14. Maintenance cost – Faulty gearbox

5.2.5 Preventive and corrective costs

Preventive and corrective costs in basic maintenance cost, Figs. 15 and 16 shows the preventive and corrective cost results for the healthy and faulty gearboxes in the range of hazard lifetime (LT) respectively and are tabulated in Table 4. The preventive and corrective cost data are determined based on equation (8) after divided into two parts related to C_p (preventive) and C_c (corrective). In the case of healthy gearbox, it is observed from Table 4 that the percentage of preventive cost from the total basic cost at failure point is 0.0; while for the corrective cost is 100 which is true. On the other hand, the percentage of preventive cost from the total basic cost at optimum point is 64.58%, while for the corrective cost is 35.42%. In the case of faulty gearbox, it is observed from Table 4 that the percentage of preventive cost from the total basic cost at failure point is also 0.0, while for the corrective cost is 100 which is also true. On the other hand, the percentage of preventive cost from the total basic cost at optimum point is 63.56%, while for the corrective cost is 36.44. However, both preventive and corrective costs for faulty gearbox are lower than those determined for healthy gearbox. An important notice is that the preventive and corrective cost are equal at intersect point, where the basic cost is 50.78 L.E./hr at 4507 min (healthy gearbox) and is 1.902 L.E./hr at 3251 min (faulty gearbox).

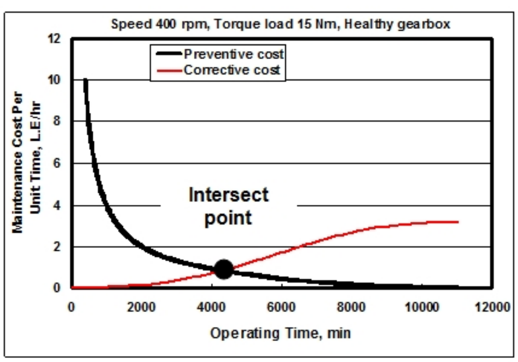

Fig. 15. Healthy gearbox, the preventive and corrective cost results

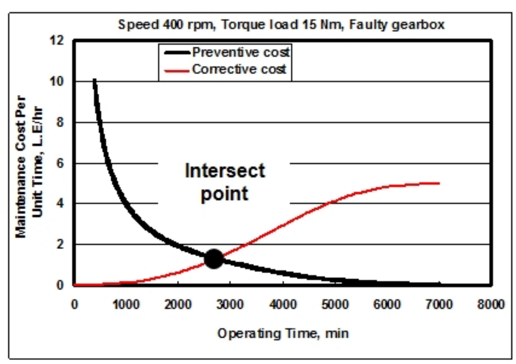

Fig. 16. Faulty gearbox, the preventive and corrective cost results

Table 4. Summarized preventive and corrective costs

No.	Gearbox condition	Replacement policy	Speed 400 rpm, torque load 15 nm basic maintenance cost						
			Total cost L.E./hr	Preventive			Corrective		
				Value L.E./hr	Time hr	%	Value L.E./hr	Time hr	%
1	Healthy-New	At Failure	3.185	0.0	11000	0.0	3.185	11000	100
		Optimal	1.57	1.014	3654	64.58	0.557	3654	35.42
		Saving	1.62	-1.014	7.346	-62.59	2.628	7346	162.59
		Intersect Point		Cost = 50.78 L.E./hr			Time = 4507 min		
2	Faulty, Crack Depth 3 mm	At Failure	5.012	0.0	6994	0.0	5.012	6994	100
		Optimal	2.47	1.57	2317	63.56	0.901	2317	36.44
		Saving	2.55	-1.57	4677	-61.57	4.111	4677	161.57
		Intersect Point		Cost = 1.902 L.E./hr			Time = 3251 min		

(-) refers to value increase

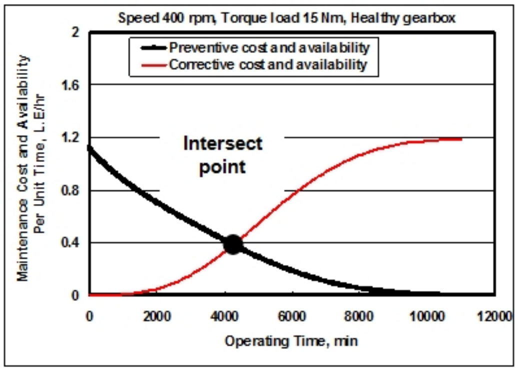

Fig. 17. Healthy gearbox, the preventive and corrective cost and availability results

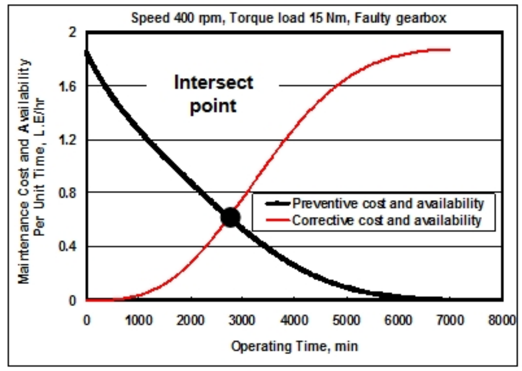

Fig. 18. Faulty gearbox, the preventive and corrective cost and availability results

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 lifetime (LT) respectively and is tabulated in Table 5. The preventive and corrective cost and availability data are determined based on equation (10) after divided into two parts related to C_p (preventive) and C_c (corrective). In the case of healthy gearbox, it is observed from Table 5 that 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 which is true. On the other hand, 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. In the case of faulty gearbox, it is observed from Table 5 that the percentage of preventive cost and availability from the total cost and availability at failure point is also 0.0, while for the corrective cost and availability is 100 which is true. On the other hand, 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. However, both preventive and corrective cost and availability for faulty gearbox is lower than those determined for healthy gearbox. An important notice is that the preventive and corrective cost and availability are equal at intersect point, where the cost is 0.420 L.E./hr at 4443 min (healthy gearbox) and is 0.625 L.E./hr at 2762 min (faulty gearbox).

Table 5. Summarized preventive and corrective costs and availability

No.	Gearbox condition	Replacement policy	Speed 400 rpm, torque load 15 Nm						
			Maintenance cost and availability						
			Total cost L.E./hr	Preventive			Corrective		
				Value L.E./hr	Time hr	%	Value L.E./hr	Time hr	%
1	Healthy-New	At Failure	1.192	0.0	11000	0.0	1.189	11000	100
		Optimal	0.709	0.520	3212	73.33	0.185	3212	26.67
		Saving	0.483	-0.52	7.788	-107.7	1.004	7.788	7.7
		Intersect point		Cost = 0.420 L.E./hr			Time = 4443 min		
2	Faulty, Crack Depth 3 mm	At failure	1.874	0.0	6994	0.0	1.872	6994	100
		Optimal	1.155	0.887	1980	76.41	0.261	1980	23.59
		Saving	0.719	-0.88	5.004	-122.4	1.611	5.004	22.40
		Intersect Point		Cost = 0.625 L.E./hr			Time = 2762 min		

(-) refers to value increase

6. SUMMARY AND CONCLUSIONS

The health monitoring of rotating machinery and power drive trains is of utmost importance in various industrial applications in industry and in automotive. 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 noise in terms of sound pressure level measurement monitoring. The technique described herein can use as a practical way to improve the return on investment in their existing CBM programs. The following conclusions are drawn as following:

1. The determination of the basic cost analysis for gear tooth crack based on the overall noise level in terms of sound pressure level, 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. This can be explained by the fact that the maintenance policy becomes close to the age replacement policy when inspection interval is large enough.

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, including repairs completed in the nacelle versus repairs done in a repair facility.

3. High availability has been bought by paying for it with more frequent intervention. It is assumed that the basic cost of maintenance was neglected, or was proportional to the repair time and therefore could be ignored. Furthermore, the saving expected results of healthy or faulty gearbox, the basic cost, availability, and maintenance cost and availability savings have been estimated. On the other hand, the operating time between failure and optimum for basic cost, availability, and maintenance cost and availability savings are all better.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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