PREDICTION FOR CONDITION MONITORING OF WEAR AND FILM THICKNESS IN A GEAR BOX

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Gears are used to transmit power and motion in mechanical, electrical and chemical process industries. Influenced by vibration, torque, temperature, lubrication & specific film thickness, the gear teeth contacts may experience change leading to unexpected failures such as wear, scuffing, pitting and micro-pitting on teeth surface. In order to avoid these damages, continuous monitoring is essential using knowledge based systems. Generic capability of artificial neural network (ANN) is exploited to formulate prediction and classification based on heuristic models of condition of lubricating oil in spur gears. Based on the loading conditions such as vibration, temperature and torque, the algorithm predicts film thickness to classify oil conditions as elastohydrodynamic (EHD), mixed wear and severe wear that helps in detecting faults in gear operation.

Keywords : *lubrication film thickness, gear failure, artificial neural network, elastohydrodynamic, condition monitoring*

1. Introduction

Monitoring behavior and condition of each of equipment in mechanical, electrical or process industries are important as they affect the overall performance of the plant. Gears are integral part of these machines used to transmit powers and motion from one mechanical unit to another and can be found in numerous applications. Like other components, gears do fail in service due to damage in teeth surface by wear, scuffing, pitting and micro pitting etc. causing reduction in teeth stiffness. Spur gears have straight teeth cut parallel to the rotational axis. The tooth form is based on the involutes curve which is generated during gear matching processes using gear cutters with straight sides. The circular pitch p of a spur gear is given as $p = 2\pi\, r_\mathrm{p}/N$ where r_p = pitch circle radius and N = number of teeth. The diametric pitch p is given by $P = N/D$ where D is the diameter of pitch circle. Gears need to be inspected periodically for sound, vibration and development of cracks (if any), teeth, and bearings. Gear failures are generally bending, fatigue, contact fatigue, wear and scuffing. The above mentioned faults in gear can be detected by monitoring vibration, torque, and temperature and lubrication film thickness continuously or online. Due to the damage on teeth surface vibration, torque, temperature of gear shaft increases and condition of oil film thickness change to mixed wear, severe wear or EHD. An EHD condition of lubricating oil favours smooth rotation of gear shaft. Thus to carry out the failure analysis of gear, vibration, torques and temperature is considered to be Inputs whereas oil film thickness may be taken as output measurement. Dudley [2] provided relation between

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pitting initiation life and contact stresses and explained the mechanism of lubrication and development of film thickness. Kubo et al. [3] proposed scuffing models using Blok-Kelly's flash temperature formula. Gear teeth are subjected to enormous contact pressures on the order of the ultimate tensile. Strength of hundred steels, yet they are quite successfully lubricated with oil films that are $< 1\,\mu$m thick. The fortuitous property of lubricant makes this possible to increase viscosity dramatically with increase in pressure. The molecular adsorption of lubricant onto the gear tooth surface causes it to be dragged into the inlet region of contact where its pressure is increased due to convergence of surfaces. Increase in viscosity helps lubricant to calculate min film thickness occurring at the exit of contact. But this doesn't explain load sharing, friction, scuffing temperature etc. Estimation or measurement of lubricating oil film thickness has been carried out by many researchers to predict healthy or unhealthy condition of the machine. ANNs have been applied in automated detection and diagnosis of machine conditions [4, 5]. For smooth running of gears, proper lubrication is to be done. Lubricants tend to degrade over a period of time and lose their lubrication properties due to chemical breakdown and become contaminated by built up particles caused by wear [6]. In order to predict and overcome wear-related damage progression in gear transmission systems, various condition monitoring techniques have been developed in past, which includes vibration, acoustic emission, oil/wear and sound analysis [7, 8]. Under typical operating condition, the lubricant film separating the contacts is very thin, usually of the same order of magnitude as the surface roughness, which may cause breakdown. In these methods, lubricant properties play an important role, since they have strong influence on film thickness [9]. A simple estimate of the thickness of the lubricating film in a typical pair of spur gears was presented on the basis of classical smooth body isothermal, EHD lubrication theory by Olver [10]. Effect of rise in temperature of lubricant on gear failure was discussed by Hohn [11]. Thus in order to answer the above mentioned unresolved issues, knowledge based modeling and algorithm [12–13] through ANN is envisaged in this research work. ANN is used here to characterize the causes of the gear failure [14–16] in terms of classifying oil film thickness with inputs such as vibration, torques and temperature. Standard feed forward networks using back propagation and Kohonen's Self Organizing Maps (SOM) are envisaged to estimate/classify oil film thickness for condition monitoring of satisfactory gear operation and thereby resolving the faults diagnosing issues.

2. Procedure

2.1. Experimental studies

The main objective of the study is to find whether the gear box is running in EHD, mixed wear or severe wear lubrication mode. The rotating machine containing the spur gear is fitted with required sensors to measure torque, vibration and temperature. The signals from these sensors are acquired using a four-channel data acquisition card. The schematic diagram of the experimental study is given in figure 1. The arrangement consists of two parallel shafts and two spur gears made up of En 24 steel without any heat treatment. The gears have teeth module of 5 mm and has pressure angle of 20°. Two love joy coupling connect the driver and driven shaft to the gearbox. The driving shaft is connected to a 5HP three-phase induction motor, which transmits power to it. Variable frequency drive (VFD) is connected to the motor in order to vary the speed and torque as per the requirement. The

Item	pinion	wheel
Center distance (mm)	150	150
Pitch diameter (mm)	100	200
Module	5	
Number of teeth	20	40
Face width (mm)	25	25
Pressure angle (°)	20	20
Gear ratio	2	
Material Properties		
Young's modulus (N/mm^2)	2×10^5	
Poisson ratio	0.3	
Material	En 24	
Brinell hardness number (BHN)	230	

Tab.1: Dimension and specifications of gear box used in experiment

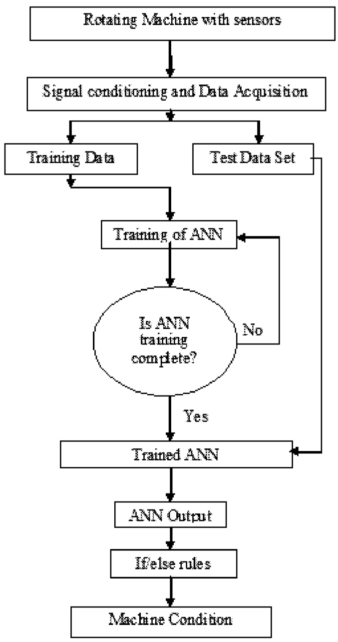

Fig.1: Flow chart of condition monitoring of gear operation

Element	Min %	Max %
Carbon	0.35	0.45
Silicon	0.1	0.35
Manganese	0.4	0.7
Nickel	1.25	1.75
Chromium	0.9	1.3
Molybdenum	0.2	0.35

Tab.2: Chemical composition of En 24 steel

dimensions and specifications of the gears are provided in Table 1. Chemical compositions of the material of construction are given in Table 2. To study the relationship of lubricant film thickness with change in torque, a special setup has been made to apply mechanical load. An arm is bolted to the underside of the test bearing and weights are added at the end of this arm. When weight is added there is a change in the torque of the system. This method is simple and effective. Torque can be varied as per the requirement by adding or removing weights.

2.2. Instruments and sensors

A commercial 4-channel data acquisition module NI9233 was used to acquire the vibration data from left and right bearing of the gearbox. The vibration data from the gearbox bearing was measured by using K-Shear@ accelerometer. The four input channels simultaneously digitize signals at rates from 2 to 50 kHz per channel built-in filters that automatically adjust to the sampling rate. The type 8702B500 series side connector and type 8704B500 top connector accelerometer series use a unique shear mode sensing element made of stable quartz crystals. The oil bath temperature was measured for every speed during the test conditions. A RTD sensor was used to measure oil temperature. The RTD was introduced in the gearbox through an opening in the top of the casing. The location for acquiring oil temperature was adjacent to the gear mesh position. AC variable drive with SK model number for 5HP three phase inductions motor was used to study speed at different frequencies. Same setup is used to study load test experiments.

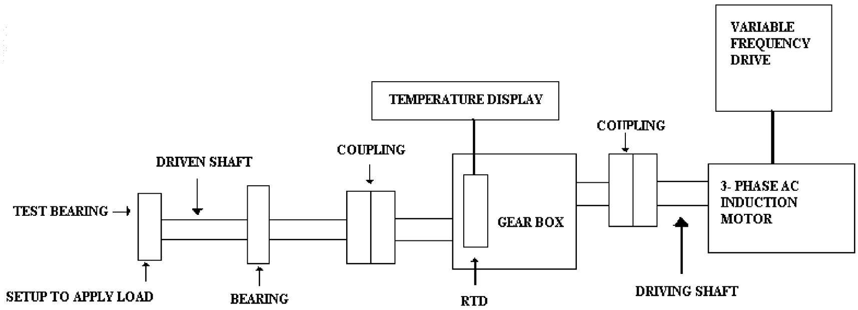

Fig.2: Schematic representation of experimental set-up/procedure

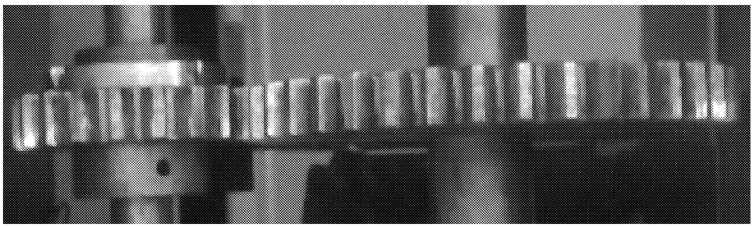

Fig.3: A pictorial view of spur gear used for the experiment

2.3. Experimental procedure

The gearbox was operated for 8 hours a day for 42 days under accelerated load conditions. The torque on the gear was increased to 1.5 times of allowable nominal value in order to initiate wear in a short period of time. Also the oil used SAE30 without anti-wearing property. The data acquisition was done using software Dewesoft version 7.0.2 for collecting vibrational signals at a sampling rate of 1000 samples/sec. MATLAB R-2008a version 7.6.0.324 was used to create a simulation model of neural network. The model consists of a forward network followed by if-then logic.

2.4. Mathematical principle

Lubrication is used to prevent direct tooth contact, to reduce friction, to prevent high vibration levels and to remove heat generated in meshing and thus saves the gear from corrosion. Analysis of film thickness involves relative motion between two rough surfaces separated by a lubricant film which when subjected to high contact pressure and sliding undergoes an increase in temperature and change in its physical properties. Under typical operating condition, the lubricant film becomes very thin, usually of same order of magnitude as the surface roughness that may cause breakdown. Thus properties of lubricant play important role and influences film thickness. Table 3 shows the properties of the lubricant oil (SAE 30) used in this setup.The damage of gear tooth occurs under three circumstances: (a) when the specific film thickness, defined as the ratio between combined roughness and lubrication film thickness, becomes greater than equal to 3 or $\lambda \geq 3$ (b) when the specific film thickness is found to be in the range of $1.4 \leq \lambda < 3$ and (c) when the specific film thickness becomes less than 1.4, i.e., $\lambda < 1.4$. The first condition indicates that the gear is operational under ideal full film or EHD lubrication. According to the second condition, mixed wear lubrication and some wear is predicted. If third condition prevails, it is understood that the gear is operating under boundary lubrication and severe wear can happen in this regime. Thus for smooth running of the system, λ should be sufficiently large. Oil film thick can be calculated using following formula [8]

$$h_{\min} = \frac{1.6\,\alpha^{0.6}\,(\eta_0\,u)^{0,7}\,(E')^{0.03}\,\varrho^{0.44}}{W^{0.13}}\ , \tag{1}$$

where α is pressure viscosity coefficient; η_0 is absolute viscosity in centipoises; u is peripheral velocity; E' is modulus of elasticity; ϱ is effective radius of curvature and W is nominal tooth force per unit width. The combined roughness R is calculated as (2)

$$R = \frac{R_1 + R_2}{2}\ , \tag{2}$$

where R_1 and R_2 are root mean square values of pinion and gear surface roughness. As seen above, roughness is an important parameter to be measured to calculate the specific film thickness, λ. Combined surface roughness of the two gears has been calculated using a comparator once in every 7 days. Thus the specific film thickness can be defined as

$$\lambda = \frac{h_{\min}}{R}\ . \tag{3}$$

S.No	Lubricant property	Values
1	Density	0.8782 kg/m^3
2	Kinematic viscosity	40 °C – 7.5 centistokes
3	Viscosity index	158
4	Flash point	202 °C
5	Pour point	158 °C
6	Pressure viscosity coefficient	3.19×10^{-8} Pa^{-1}

Tab.3: Properties of Lubricant oil (SAE 30)

3. Application of artificial neural network

3.1. Back propagation

Artificial Neural Networks (ANNs) are nowadays being used for automated detection and diagnosis of machine conditions. Among different types of ANNs back propagation method is popular and is used to model (estimate) specific film thickness. Back propagation consists of an input layer of the source nodes, one or more hidden layer and an output layer.

The number of input and output layer depends on number of input/output in the problem (in the present case 4 inputs and one output). The hidden layer affects the generalization capability of the network. Figure 4 shows the typical topology of back propagation architecture. For a better understanding, the back propagation learning algorithm can be divided into two phases: propagation and weight updation. Propagation involves following steps:

- Forward propagation of a training pattern's input through the neural network in order to generate the propagation's output activations;

– Back propagation of the propagation's output activations through the neural network using the training pattern's target in order to generate the incremental output (deltas) of hidden neurons.

The activation function used in calculation the outputs from hidden and output layers here is logistics (log-sigmoid) as given by

$$f(x) = \frac{1}{1 + e^{-x}} \,, \tag{4}$$

For each of weight update the following steps are followed
– Multiply its output delta and input activation to get the gradient of the weight;
– Bring the weight in the opposite direction of the gradient by subtracting a ratio of it from the weight.

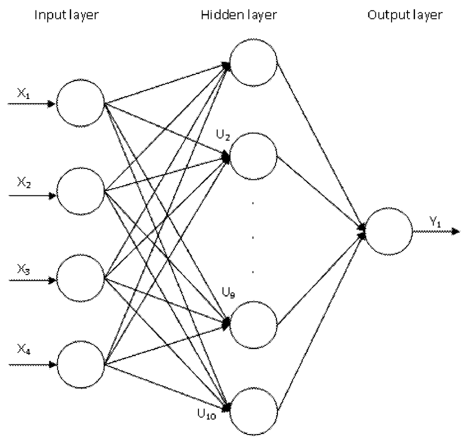

Fig.4: Architecture of ANN back propagation network structure

The above two steps are repeated until the performance of the network is closest to the target output. After getting predicted lubricant film thickness, if then rules are used to diagnose the cause of failure or wear.

3.2. Kohonen's self organizing maps

In order to characterize the causes of failure (wear) of gear in terms of relationship between certain parameters and lubricant film thickness Kohonen's self organizing maps (SOM) is used in the present case. The capabilities of SOM are exploited to classify the causes of wearing of tooth (gear) under three different circumstances (based on ranges of λ), namely, EHD, mixed wear and severe wear lubrication.

3.3. Data preparation

For the experimental setup the following variables were considered as inputs to net:
(a) Vibration data – consisting of vibration acceleration from the right and left bearing (two inputs);
(b) Temperature from RTD sensor located near the gear mesh position (one input);
(c) Torque of the motor from the VFD by calculating mechanical power (one input).

The roughness parameters were calculated and the output from the back propagation net is lubricant film thickness. Whereas the output from SOM is either of the causes of failure or wear. The lubricant film thickness thus calculated using back propagation is subjected to diagnose wear of gear-tooth with the help of if-then rules.

The first experiment using the available data involved the exploitation of ANNs to provide inferential information of specific film thickness based on input data. ANNs ate trained with data obtained from gearbox in the initial few weeks when there was no wear on the gear to have EHD lubrication with normal wear. When En-24 material was used with SAE 30 oil, to initiate wear, the data collected in a short span of time was used for classifying under mixed wear condition. After many days of operation, the set of data collected from the system was used for analysis of severe wear. The network can thus be trained on the complete data set and tested on the subsets accordingly. About 70 % of data is used for training, 20 % of data is used for validation and 10 % is used for testing.

3.4. Train/test strategy

3.4.1. Training with back propagation

The input data set is normalized and is subjected to co-relation data test on various parameters using statistical methods. The training method adopted is termed as being of a supervised nature. The particular network consists of an input layer with four input neurons, a hidden layer with 8 neurons and an output layer with one neuron. The network is presented with a set of input data along with a desired output. The network shows several training examples repetitively and attempts to adjust its interconnecting weights in order to minimize the error between its output and target over the entire training data set The ability of the network to learn and generalize the co-relation between inputs and targets is then tested by presenting the network with data and analyzing the network response in terms of the accuracy of its output compared with desired output.

The data used for constructing, training and testing the ANNs suggests the training file to be presented in a random fashion. This helps to optimize the in-training process and avoids from being trapped in local minima.

3.4.2. Training with self organizing map

The data set is normalized and is subjected to principal component analysis. The data set (consisting of sub-sections of three different conditions) comprising of four inputs and one output is used to train Kohonen's network consisting of an input layer of 5 neurons the 5-node input layer is fully connected to a 5×3 Kohonen layer architecture being arrived at through trial and experiments until it provided satisfactory network performance. The unsupervised training of SOM network attempts to subdivide the training data into categories by modifying the weights on the various connections from the input layer to the Kohonen layer nodes in order to reflect subsets within the training data. When individual data subsects are presented during test phase, the difference between the categories of input data is reflected in the distribution of the active nodes throughout the map (Kohonen layer).

In the present case, the entire data set is presented to network that attempts to characterize the data set in terms of identification of any subset within the entire data set. In order to test the network the individual subsets of data representing the gear operation under EHD, mixed wear and severe wear conditions are presented to the trained network whose response was analyzed in terms of distribution of active nodes. For each particular train/test example, only one node becomes active (closest/nearest to the input vector in Euclidean space).

4. Results and discussion

4.1. Experimental

Figure 5 shows the condition monitoring procedure for gearbox where data from sensors, connected to gearbox, can be transferred through MODEBUS from data acquisition to an interfaced computer terminal. The condition of gearbox is constantly monitored and analyzed through this method. With increase in operating time starting from 0 hrs, the data related to the vibration of gearbox also starts varying. It was found that the vibration at the start of experiments is far less compared to the same at the end or final stages of experiments. Also, with increase in load on gearbox, the vibration acceleration reduced as can be seen in Figure 6. This is due to the fact that increase in load reduces the vibration characteristics of the gearbox. Increase in temperature affects the physical properties of oil that in turn affects the condition of gear teeth. As the separating film becomes thinner the wear on spur gear becomes more and more. This is due to higher values of loads and temperature. Thin lubricant film leads to removal of material from mating surface causing

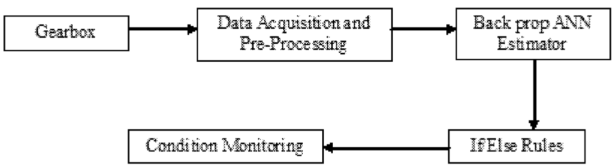

Fig.5: Condition monitoring procedure

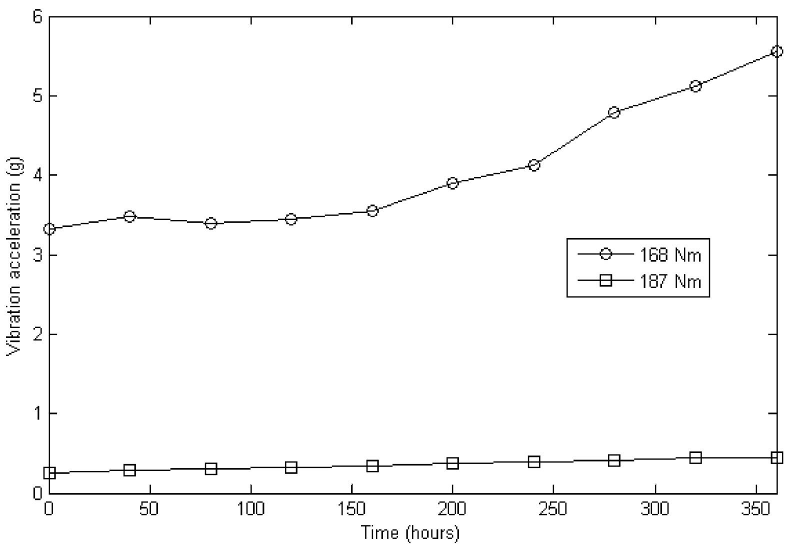

Fig.6: Observed variation in vibration acceleration during operation of gear under different torques (circles for 168 Nm and squares for 187 Nm)

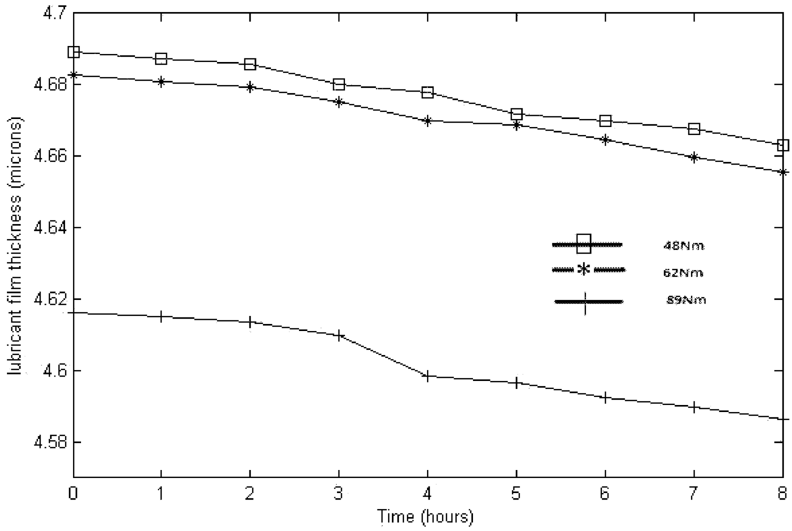

Fig.7: Observed variation in lubricant's film thickness during operation of gear under different torques (squares – 48 Nm; asterisk – 62 Nm; + symbol – 89 Nm)

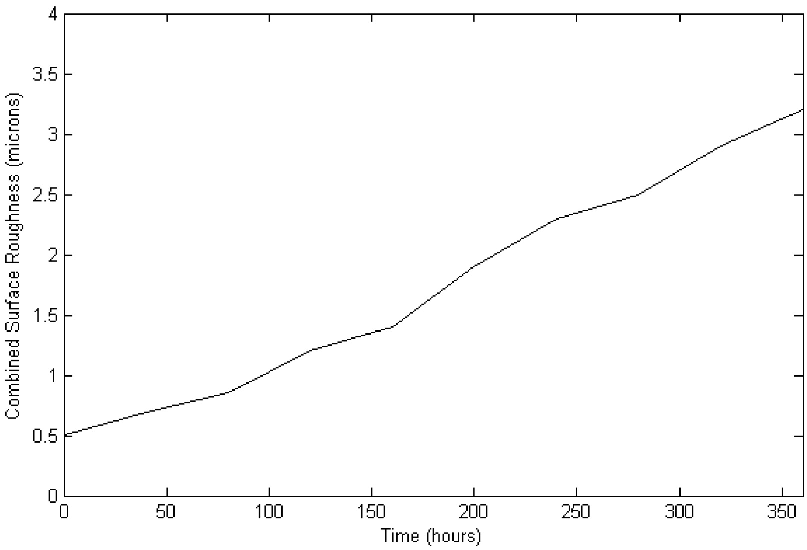

Fig.8: Variation of combined surface roughness during gear operation

gear problem. Condition of gearbox can be related to specific film thickness which gives an indication of contact severity or lubricant film breakdown.

It is evident from Figure 7 that an increase in load results in reduction of oil film thickness. Calculation related to measurement of surface roughness is instrumental and is helpful in finding film thickness. The combined roughness of two gears increases with increase in service time as it can be seen from Figure 8.

Specific film thickness can be used to determine damage severity from normal to severe wear condition by taking into account oil temperature, load on gearbox and vibration acceleration. Figure 9 shows an increase in oil temperature with increase in service time. The same oil was used throughout the experiment. This reveals that oil temperature increases with increase in torque and operating time.

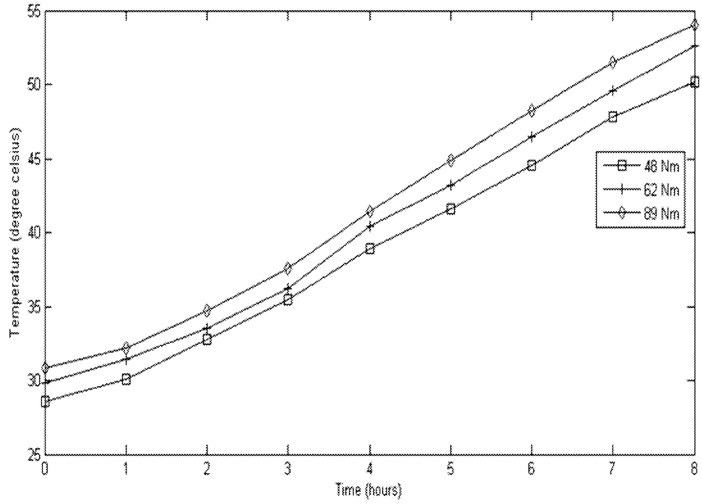

Fig.9: Observed variation in temperature during gear operation under different torque (square – 40 Nm; + symbol – 62 Nm; circle – 89 Nm)

4.2. Simulation

Simulation of the network was done using simulink of Matlab. 'If then' block was used to verify the condition of gearbox based on the specific film thickness. This was then tested by test data set.

4.2.1. Back propagation

ANNs of the back propagation type were trained using training data set. Figure 10 illustrates the results for a back propagation ANN.

The RMS error is plotted against number of epochs of training. After 1000 iterations the error comes down and flattens out revealing no more significant change in error with further increase in number of epochs. The testing and validation errors are also less as seen from close proximity of the curves. Thus this heuristic model can be used in the field of condition monitoring as gear problems could be identified and alarmed through a comparison of actual and estimated variables with appropriate messages being generated if the estimated levels of any input variables differ significantly from nominal level over a period of time.

If-Then logics in conjunction with estimated and observed data are helpful in order to diagnose faults in gear operation when the network was tested with input data set [34.3000; 22.3105; 15.2000; 19.0800] and targeted output [4.2921] the network yielded a predicted output of 4.1121.

4.2.2. Self organizing maps (SOM)

Figure 11 shows distribution of active nodes and clusters of data accumulated around those nodes. When the net was tested with input data set of [34.3000; 22.3105; 15.2000;

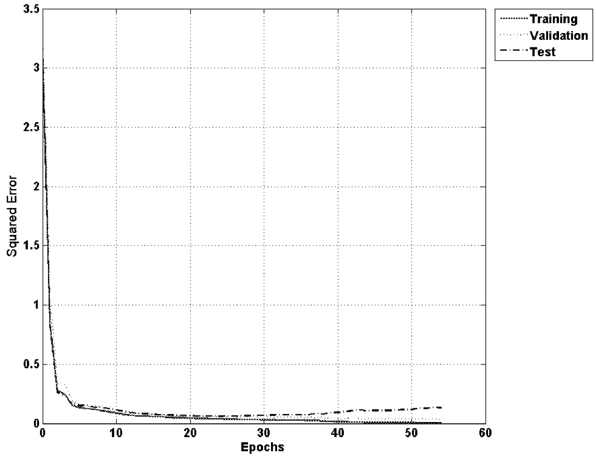

Fig.10: Change in squared error with number of epochs during training (solid line), validation (dotted line), testing (dash dot line)

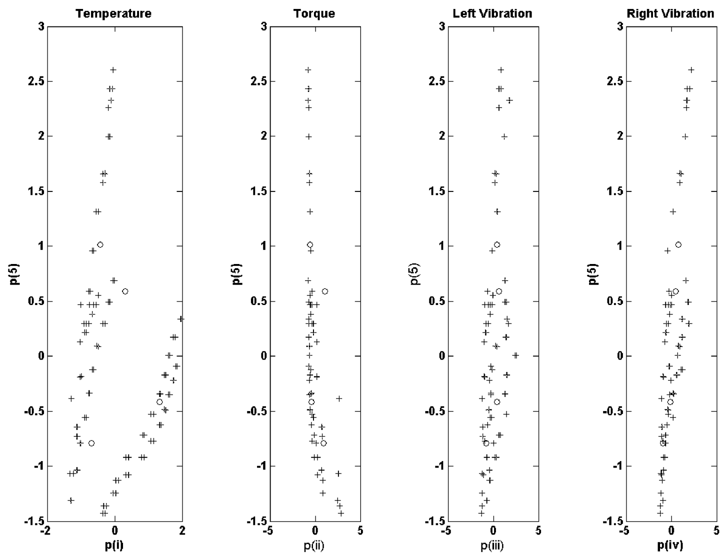

Fig.11: Clustering of input data set nearer to neural nodes with respect to parameters (p(i) is temperature; p(ii) torque; p(iii) left side bearing vibration; p(iv) right bearing vibration and p(v) is specific film thickness)

19.0800; 4.2921] the network yielded an output of [(1, 1) 1]. The output represents that specific film thickness λ has a value that lies in first region (EHD) and the gear condition is okay. Figure 12a shows a three dimensional plot of weight vectors using SOM one dimensional network. The red dots are the neuron's weight vectors, and the blue lines connect each pair within a distance of 1. Figure 12b illustrates a three dimensional plot of weight vectors using SOM 2-dimentional architecture. Each neuron is represented by a red dot at the location of its two weights. Initially all the neurons have the same weights in the middle of the vectors, so only one dot appears. Now we train the map on the 70 % vectors for 1 epoch and re-plot the network weights. After training, it was noted that the layer of neurons has begun to self-organize so that each neuron now classifies a different region of

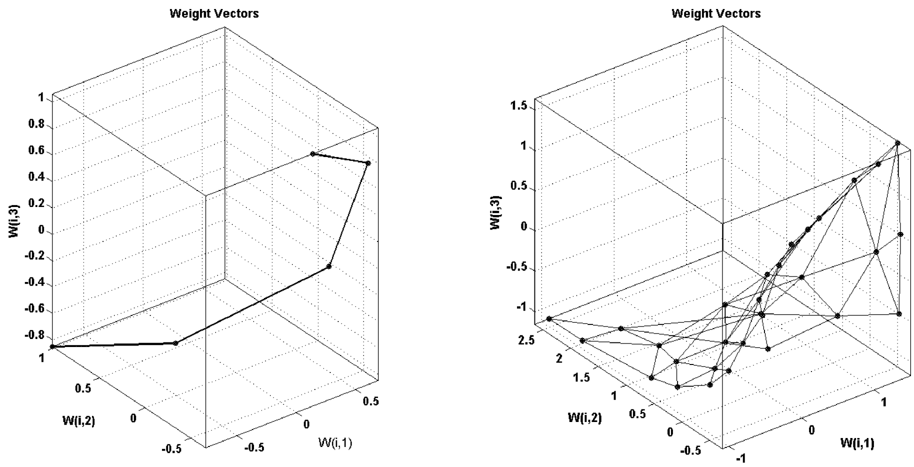

Fig.12: Mapping of weight vectors connecting : (a) each pair of neurons; (b) each pair of neurons in different epochs during training

the input space, and adjacent (connected) neurons respond to adjacent regions. The SOM map is tested to classify the above input data set and the net yielded an output of [(3, 1) 1] revealing that the tested vector lies nearer to 3rd neuron and has classified the gear condition as 1 or as EHD type.

5. Conclusion

Failure of gear operations are categorized into three separate domains based on lubrication conditions : (1) elasto hydro dynamic, (2) mixed wear and (3) severe wear. ANN models with back propagation network and Kohonen's Self Organizing Maps are formulated separately for diagnosing failure of gear operations. The networks are trained, validated and tested with real time data as vibration, temperature and torque from gear experiment. The results revealed that the oil temperature increases with increase in torque and operating time. The relationship between the load on the gearbox and lubricant film thickness was estimated. The lubricant film thickness was found to reduce when load was added to the system. Specific film thickness (λ) can be used to determine damage severity from normal to severe wear condition by taking into account oil temperature, load on the gear box and vibration acceleration. Vibration (in terms of acceleration), along with specific film thickness provide good diagnostic information to estimate the wear severity on the gears.

The combined roughness on the gear teeth increases with increase in operating time. The information gained through the use of ANN could be used in on-line condition monitoring of the gearbox through estimating the wear on the gear. The architecture and topology of the network though system specific, can be used to predict causes of failure of gear operation.

References

[1] Radovich J.L.: Gears, Handbook of Lubrication (Theory and Practice of Tribology), Vol. II, Booser, E.R. (Ed.), CRC Press, Boca Raton, FL, pp.539–564, 1984

[2] Dudley D.W.: Gear wear, in Wear Control Handbook, Peterson M.B. and Winer W.O. (Eds.), The American Society of Mechanical Engineers, New York, pp. 755–830, 1980

[3] Kubo A., Townsend D.P.: Gear lubrication, in Dudley's Gear Handbook, Townsend D.P. (Ed.), McGraw-Hill, New York, 15.1–31, 1991

[4] Samanta B., Al-Baulshi K.R., Al-Araimi S.A.: Artificial neural network based Fault diagnostics of rolling element bearings using time domain features, Mechanical Systems and Signal Processing 17 (2), pp. 317–328, 2003
[5] Samantha B.: Gear fault using artificial neural networks and support vector machines with genetic algorithms, mechanical systems and signal processing 18, pp. 625–644, 2004
[6] Davis A.: Handbook of condition monitoring, London, Chapman & Hall; 1988
[7] Drosjack M.J., Houser D.R.: An experimental and theoretical study of the effect of simulated pitch line pitting on the vibration of a geared system, ASME publication report 7-DET-123, 1997
[8] Sung C.K., Tai H.M., Chen H.M.: Locating defects of gear system by the technique of wavelet transform, Mech Mach Theory, 2000
[9] Amarnath M., Sujatha C., Swarnamani S.: Experimental studies on the effects of reduction in gear tooth stiffness and lubricant film thickness in a spur geared system, Tribology International 42, pp. 340–352, 2009
[10] Dowson D., Higginson G.R.: Elastohydrodynamic lubrication, New York, Pergamon Press Ltd., 1977
[11] Bartz J.W.: Lubrication of gearing. London: mechanical Engineering publication Ltd., 1993
[12] Hõhn B.R., Michaelis K.: Influence of oil temperature on gear failures, Tribol Int, 37:103–9, 2003
[13] Haykin S.: Neural Networks: A Comprehensive Foundation, Macmillan College Publishing, New York, 1994
[14] Ying Peng, Ming Dong, Ming Jian Zuo: A review, Current status of machine Prognostics in Condition based maintenance, Int. J. Adv. Manuf, Technol., Springer, 2010-s00170-009-2482-0, 2010
[15] Booth C., McDonald J.R.: The use of Artificial Neural Networks for Condition Monitoring of Electrical Power Transformers, Neurocomputing, 23, pp. 97–109, 1998
[16] Peng Z. Kessissoglou N.: An integrated approaches to fault diagnosis of machinery wear debris and vibration analysis, Wear 225(7–12), pp. 1221–32, 2002
[17] Dempsey P.J.: Wear damage detection using oil debris analysis, NASA TM 211492, ARL-TR-2682, 2002
[18] Ebersbach S., Peng Z., Kessissoglou N.J.: The investigation of the condition and faults of a spur gearbox using vibration and Weardebristechniques, Wear, volume 260, issues 1–2, 2006

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