Iterative Self Organized Data Algorithm for Fault Classification of Mechanical System

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Abstract - ***The challenging issue for mechanical industry is to develop fast & reliable fault diagnosis systems before total breakdown of machine. Fault diagnosis & classification of faults of mechanical systems is a difficult task. It improves productivity & reduces cost of production. This paper presents an approach for classification of commonly observed faults in gears of mechanical system. These faults include weared gear, gear with one tooth broken & gear with crack on one tooth. The Power Spectral Density (PSD) of the vibration signals of faulty gears is used to construct feature vectors. Principle component analysis (PCA) is used to reduce the dimensions of feature vector. The Routine checkup of the machine generates Known fault vectors. The ISODATA (Iterative Self Organizing Data Analysis Technique) [1] classifies fault vectors along with newly collected fault vector. If the fault is different from the previously identified fault a new fault cluster is created else new fault belongs to one of previously identified fault clusters.***

1.0 INTRODUCTION

The complexity of engineering systems increases the danger of failure of system/machine. This affects productivity, & environment. With complex machines the maintenance cost increases. Hence fast & precise identification of faults is essential.

Fault can be defined as an abnormal state of a machine or system such as malfunction or dysfunctions of part or an assembly .[3]

The critical element in any machine is Gear. The study carried out in Germany, on samples of gears shows that 19-24% failure of mechanical system is usually because of mishandling or inadequate maintenance. This study also shows that damage or failure caused by gears & bearings is in the ratio of 3:1.about 60% failures are because of faults in gear; 19% failures are because of faults in bearings & 10% failures are because of faults in shafts. [4]

The process of fault diagnosis consist of fault detection & classification of fault. The faults in gears can be detected by using vibrations generated from it.

The vibration analyst of a machine requires detailed knowledge of a mechanical system, dynamic properties of machine along with history of it's maintenance .

This paper provides the approach of identifying the type of fault occurred in gear system. This provides novel approach of using pattern recognition algorithm named as ISODATA for classification of faults in gear system. The computing efficiency of the classifier is improved by reducing feature vector dimension using Principal component analysis. The method suggested above helps inexperienced machine user to detect various fault in machine under observation.

The present methods of fault classification includes use of Learning Machine,. Hoelder Exponents, PCA, ANN, Support Vector Machine, Generalized Discriminant Analysis, WT-ANN, Case Based Reasoning etc.

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2.0 THE ISODATA ALGORITHM [1]

ISODATA stands for *Iterative Self-Organizing Data Analysis Techniques*. This is a more sophisticated algorithm which allows the number of clusters to be automatically adjusted during the iteration by merging similar clusters and splitting clusters with large standard deviations.

We first define the following parameters:

1. K = number of clusters desired;
2. I = maximum number of iterations allowed;
3. P = maximum number of pairs of cluster which can be merged;
4. Θ_N= a threshold value for minimum number of samples in each cluster can have (used for discarding clusters);
5. θs = a threshold value for standard deviation (used for split operation);
6. θc= a threshold value for pairwise distances (used for merge operation).

The algorithm:

Step1: Arbitrarily choose k (not necessarily equal to K) initial cluster centers:
M_1, M_2, ………….., M_k from the data set { Xi , i=1, 2…….,N}

Step2: Assign each of the N samples to the closest cluster center:

$$X \sim \omega_j \quad if \quad D_L(X, M_j) = max\{D_L(X, M_i), \; i = 1, \cdots, k\}$$

Step3: Discard clusters with fewer than θN members, i.e., if for any j , $N_J < \theta_N$ then discard Wj and k. k-1

Step4: Update each cluster center:

$$M_j = \frac{1}{N_j} \sum_{X \sim \omega_j} X \quad (j = 1, \cdots, k)$$

Step5: Compute the average distance Dj of samples in cluster Wj from their corresponding cluster center:

$$D_j = \frac{1}{N_j} \sum_{X \sim \omega_j} D_L(X, M_j) \quad (j = 1, \cdots, k)$$

Step6: Compute the overall average distance of the samples from their respective cluster centers:

$$D = \frac{1}{N} \sum_{j=1}^{k} N_j D_j$$

Step7:If k ≤ k/2 (too few clusters), go to Step 8; else if k>2k (too many clusters), go to Step 11; else go to Step 14.
(Steps 8 through 10 are for split operation, Steps 11 through 13 are for merge operation.)

Step8: First step to split. Find the standard deviation vector ∑ j = [σ1(j) ,….., σ n(j)]T for each cluster:

$$\sigma_i^{(j)} = \sqrt{\frac{1}{N_j} \sum_{X \sim \omega_j} (x_i - m_i^{(j)})^2}, \quad (i = 1, \cdots, n, \ j = 1, \cdots, k)$$

where ,
$m_i^{(j)}$ is the i^{th} component of M_J and σ_i is the standard deviation of the samples in Wj along the i^{th} coordinate axis. Nj is the number of samples in Wj.

Step9: Find the maximum component of each∑ j and denote it by σ_{max} (j) ; Do this for all

$$j = 1, \cdots, k$$

.

Step10: If for any σmax(j) , (j =1,…..,k) , all of the following are true

$$\sigma_{max}^{(j)} > \Theta_S$$

,

$$D_j > D$$

,

$$N_j > 2\Theta_N$$

Then *split* Mj into two new cluster centers Mj(+) and Mj(-) by adding ±δ to the component of Mj corresponding to σmax(j) , where δ can be α σmax(j) , for some α >0. Then delete Mj and let k. k -1. Go to Step 2 else Go to Step 14.

Step11: First step to merge. Compute the pairwise distances Dij between every two cluster centers:

$$D_{ij} = D_L(M_i, M_j), \quad (for\ all\ i \neq j)$$

and arrange these k(k-1)/2distances in ascending order.

Step12: Find no more than P smallest Di j 's which are also smaller than θC and keep them in ascending order:

$$D_{i_1 j_1} \leq D_{i_2 j_2} \leq \cdots \leq D_{i_P j_P}$$

Step13: Perform *pairwise merge*: for l = 1,……P, do the following:
If neither of M_i and M_j l has been used in this iteration,
Then merge them to form a new center:

$$M = \frac{1}{N_{i_l} + N_{j_l}} [N_{i_l} M_{i_l} + N_{j_l} M_{j_l}]$$

Delete M_{il} and M_{jl}, and let k. $\leftarrow$ k -1. Go to Step 2.

Step14: Terminate if maximum number of iterations I is reached. Otherwise go to Step 2.

The ISODATA algorithm is more flexible than the K-mean method. But the user has to choose empirically many more parameters listed previously.

3.0 EXPERIMENTAL SET UP

It consists of an half HP induction motor mounted on rigid steel structure. Driven gear is mounted on motor shaft. The load is coupled to driver gear by driven gear. The machine runs at constant speed of 1470 RPM at constant load (80 % of rated capacity). Both gears are identical having 62 teeth. Different Fault conditions were created on driven gear typically weared gear, cracked tooth, broken tooth. Figure 1 shows photograph of the model of experimental set up kept on rubber pad. These pads are used to reduce weak foundation fault effects on feature vector sets.

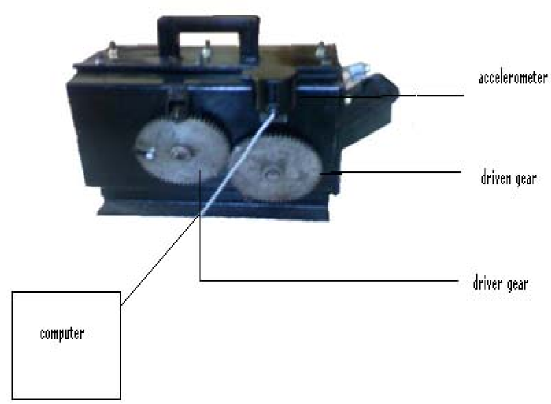


Figure 1: Model of experimental set up

Using this set up the faulty vibration signatures are collected by accelerometer & stored in memory of computer.

3.1 Artificially Creation of Faults on Gear Tooth.[5]

The common faults observed in Spur gear are:

3.1.1 Weared gear : This fault was created by filing the gear teeth in both direction of rotation to remove the material from teeth up to 500 micron.

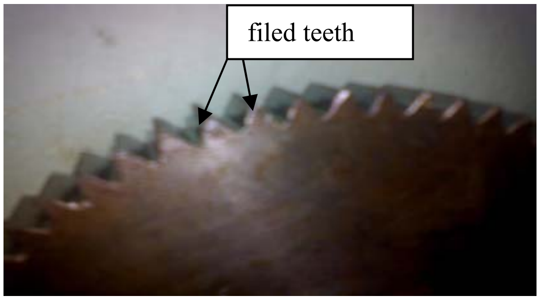


Figure 2: Weared Gear

3.1.2 One Tooth Broken Or Missed: To get signal of this condition ,the gear tooth was removed by hack-saw blade.

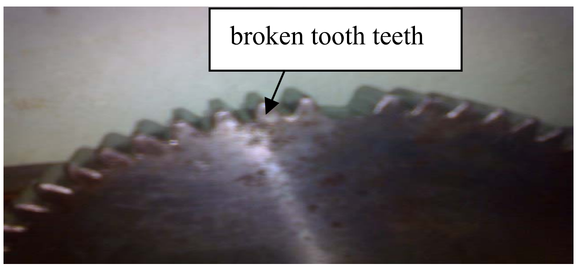


Figure 3: Gear with One Tooth Broken or Missed

3.1.3 Crack On One Tooth: The signal of this condition is obtained by cutting the tooth with hack-saw blade at the root of the tooth in the direction of rotation.

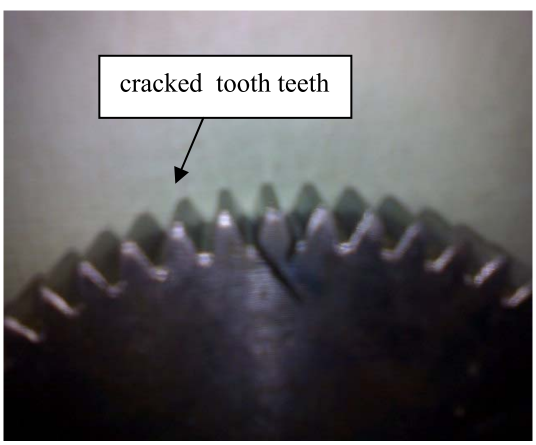


Figure 4: gear with crack on one tooth

3.2 Construction of Accelerometer

The accelerometer used in this set up uses ring type crystal as a sensor which has a mass attached to one of its surfaces. When the mass is subjected to a vibration signal, the mass converts the vibration (acceleration) to a force, this then being converted to an electrical signal representative of the incoming vibration signal as shown in following figure. This is the basis of the Accelerometer. The accelerometer output may then be processed to provide the instantaneous velocity and displacement signals.

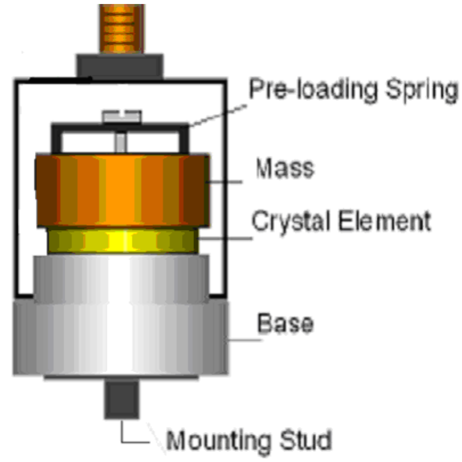


Figure 5: Accelerometer

3.3 PROCEDURE FOR RECORDING SIGNAL

3.3.1 The motor is run at the rated speed of 1470 rpm. Load is applied by providing sufficient tension to break & pulley system.

3.3.2 The accelerometer is mounted near the driven gear & its output is connected to microphone input of sound card of computer.

3.3.3 First the readings for non–defective, good lubricated gear condition are recorded using 'Gold wave' software for a period of one minute. It is stored for further analysis and comparison with other signals derived from faulty gears mentioned above.

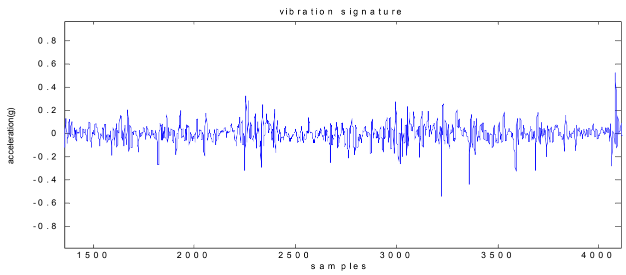
3.3.4 The non-defective gear is then removed using gear puller and replaced by faulty gears. For each faulty gear signal derived from accelerometer is recorded & stored in memory of computer in wave file format for further analysis.

3.3.5 For each reading load & speed conditions are kept constant.

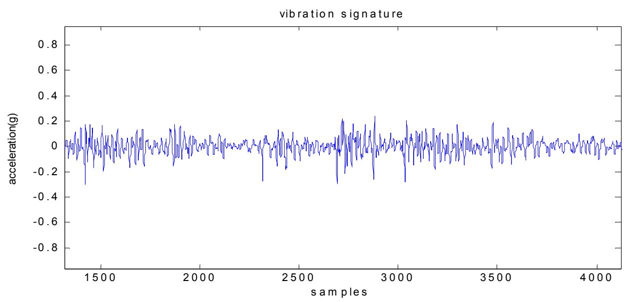
3.3.6 The accelerometer signal is sampled at the sampling rate of 44100 samples per seconds. Each sample is of 16 bit, MSB reserved for sign. Gear mesh frequency of machine under observation is 24.5 RPS x 62 teeth = 1519 Hz. The second and third harmonics shoes significant amplitude and sidebands along the gear mesh frequency harmonic. Hence sampling rate of 44100 samples per second proved sufficient throughout experimentation.

4.0 RESULTS

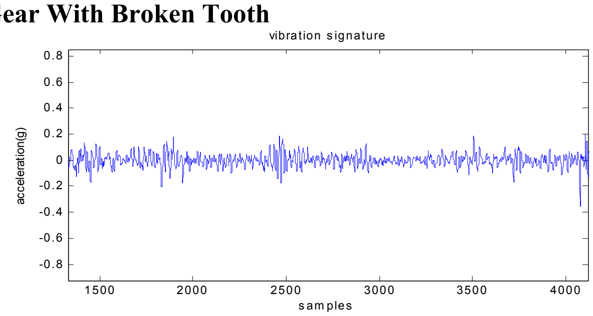
Figure 6 shows the vibration signal for each type of gear.



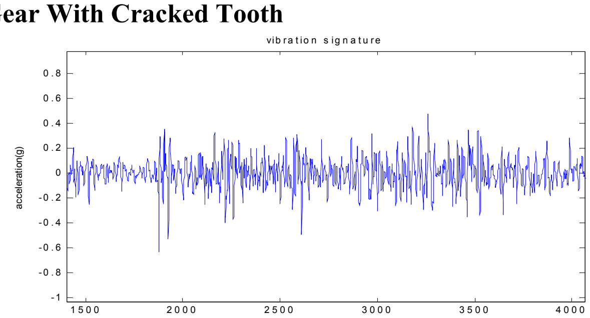
Good Gear



Gear With Broken Tooth



Gear With Cracked Tooth



Weared Gear

Figure 6: Vibration Signature

By observing above signatures/signals its difficult to recognize type of fault.

4.1 Kurtosis

The kurtosis can be used to check the distribution of signal.. Kurtosis is a measure of how outlier-prone a distribution is. The kurtosis of the normal distribution is 3. Distributions that are more outlier-prone than the normal distribution have kurtosis greater than 3; distributions that are less outlier-prone have kurtosis less than 3.

The kurtosis of a distribution is defined as

$k=E(x-\mu)4\ /\sigma4$

where,

μ is the mean of x,

σ is the standard deviation of x,

E(t) represents the expected value of the quantity

The kurtosis of good lubricated gear is low indicating normal signal distribution while other signals shows higher kurtosis indicating outlier –prone distribution. Table1 shows kurtosis of all gear signals is given in table1

Type of signal	Kurtosis
Lubricated good gear	4.8383
Gear with one tooth broken	7.4362
Gear with crack on one tooth	9.4898
Warned gear	6.8536

Table1: Kurtosis

The observations in table show different kurtosis value for each type of gear signal; but from this value we cannot predict type of fault in the gear. Hence some type of intelligent system should be used to identify the fault. This paper used ISODATA to identify the fault.

4.2 Feature Vector Generation and PCA

The feature vectors are generated by determining 256 point Power Spectral Density (PSD) of fault signal . This produces set of dimensional feature vectors from each type of class/fault signal. Figure 7 shows Power spectral density of each type of fault:

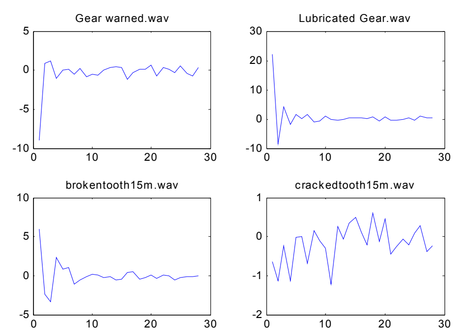


Figure 7: PSD of All Types Of Signals Of Gear Vibration.

The dimensionality of this feature vector is large & may result in to large classification or training period. Hence it is needed to reduce the dimensionality of input vector .For this Principle Component Analysis (PCA) [2] is used.

PCA removes redundant information. PCA has three effects:

4.2.1 It orthogonalise the components of input vectors ; so that they are uncorrelated with each other.

4.2.2 It orders the resultants orthogonal components (Principle Components), so that those with largest variation come first.

4.2.3 It eliminates those components which contribute least to the variations in the data set.

4.3 CLASSIFICATION OF FAULTS (USING ISODATA)

4.3.1 Classified fault database

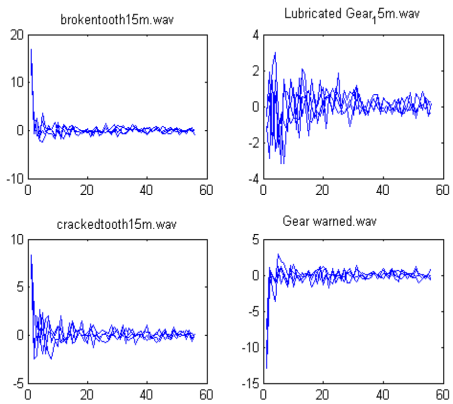


Figure 8: Classified fault database

4.3.2 Locating unknown fault

4.3.2.1 Weared Gear:

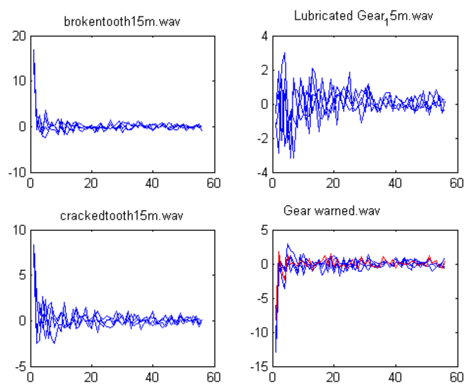


Figure 9: Classified Weared Gear Fault

4.3.2.2 Crack On One Tooth

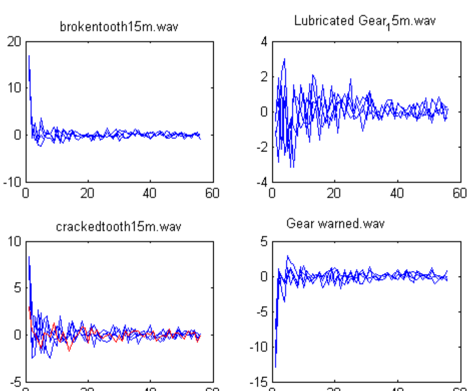


Figure 10: Classified Cracked tooth Gear Fault

4.3.2.3 One Tooth Broken Or Missed

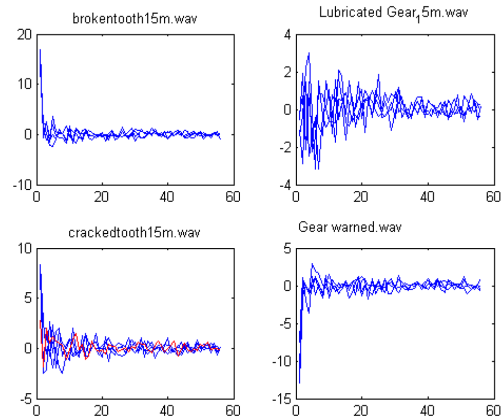


Figure 11: Classified Broken or missed tooth Gear Fault

Following table shows the success of ISO DATA Algorithm in classifying various signatures of gear fault.

Type of signal	% of success
Good , Lubricated gear	100
Warned gear	100
Gear with crack one tooth cracked	100
Gear with on e tooth broken	Failed

Table2: Success Of ISODATA

5.0 CONCLUSION

The ISODATA algorithm classifies all types of faults. On some occasions it fails to distinguish between the faults. This happens if the fault feature vectors are in close vicinity. e.g. it fails to distinguish between the signal of broken tooth & cracked tooth as depicted in fig 11 above. This is the limitation of this algorithm & it could be overcame by searching better vibration signal processing method that keep feature vectors apart .

REFERENCES

[1]. J.T. Tou, P. C. Gonzalez, 1974, *Pattern Recognition Principles*, Wesly Publication Company

[2]. Neural Network toolbox, Matlab version 6.5

[3]. Erik Olsson, Peter Funk, Ning Xiong, Fault Diagnosis in Industry Using Sensor Readings & Case Based Resoning,Journal of Intelligent & Fuzzy Systems: Applications in Engineering and Technology, Volume 15 , Issue 1 (January 2004) Pages: 41 - 46 ,2004

[4]. Martin, Detection of Gear Damage by Statistical Vibration Analysis, IMechE,Journal of Mechanical Engineering, Pages 395-401, 1992,

[5]. Patil Atul & Gawade S, Acoustic Intensity Analysis Of Gearbox & Fault Diagnosis of Gear Teeth By CBM; Proceedings of International Conference On Advances in Machine Design & Industry Automation, January 10-12,2007.