JJMIE

Volume 3, Number 1, March. 2009
ISSN 1995-6665
Pages 59 - 68

Jordan Journal of Mechanical and Industrial Engineering

Automated Maintenance Approach for Industrial Machineries by Soft Computing Techniques at Offline Monitoring Process

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Abstract

Fault diagnosis of industrial machineries become very much important for improving the quality of the manufacturing as well as for reducing the cost for product testing. In modern manufacturing scenario, a fast and reliable diagnosis system has turned into a challenging issue in the complex industrial environment. In this work, the diagnosis of gearbox is considered as a mean of health monitoring system by used lubricant. The proposed methodology has been performed on the basis of wear particle analysis in gearbox at offline stage. Possible wear characterization has been done by image vision system to interpret into soft computing techniques like fuzzy inference and neural network mechanisms. Basically, the maintenance policy has been taken with the help of fuzzy expert system, which has been described in the present work.

Keywords: Wear Particle Analysis; Fractal Mathematics; Artificial Neural Network; Fuzzy System; Image Processing System

1. Introduction

The manufacturing industries have already started on the issue of cost of equipment, maintenance, and its simultaneous services with reliability factors since the last few decades. These kinds of effects generally prevail on sectors such as; power generation, refinery, transportation and so on. Even other factors such as; parts, labor, equipment downtime, lubricant prices, disposal costs are also the primary concern in a well-run maintenance program. Machine condition monitoring has found prerequisite maintenance programs amongst all other methodologies [1]. But lubricant analysis has found one of the suitable techniques in machine monitoring processes, popularly known as wear particle analysis. Based on lubricant analysis, the diagnosis of equipments can be done properly as it involves continuous process. Lubricant analysis and its positive effects is revealed in Figure1.

Some of the reasons have been considered for economic analysis in machine monitoring system such as;

- total machine reliability
- reduction of downtime
- increased throughput
- reduced operations risks
- savings on operation and management budget
- detailed knowledge of machinery(s)
- operational excellence

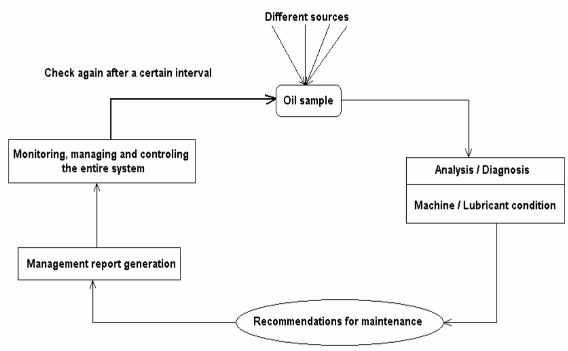

Figure1: Lubricant analysis for monitoring condition.

Maintenance of machineries and recognizing the possible faults in their entire lifecycle have been found as the most important arena in the industrial sector. After successful installation of various automatic machineries in different types of industrial level, governments have already started reviewing the economies so that the unnecessary waste of accessories can be prevented with suitable maintenance policies. Commercial advantages of maintenance have been adopted for the last few decades just to reduce the costs of the entire activities by including the original equipment features to facilitate maintenance tasks. In most industries, condition monitoring is adopted to provide the maximum possible technical solutions in on-going condition assessment, fault prediction, fault detection, location, classification and so on [2]. Some of the most standard monitoring techniques can be handled in the equipments like,

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- Gearboxes [tooth stiffness measurements, mesh modeling, detection-location-diagnosis and severity assessment of different cracks and so on]
- Aerospace structures
- Compressors
- Diesel engines
- Robotics

In the present work, fault diagnosis has been done on the basis of wear particle analysis by using some mathematical interpretations with soft computing techniques.

2. Automated Wear Particle Analysis

Wear is basically the damage to any surface that generally involves sufficient loss of materials and it may occur as a result of relative motion between that surface and the contacting substances. Wear particle investigations and fault diagnosis of different machineries are not a new topic in maintenance engineering rather in the field of tribology. This technique has already been accepted as an effective and economic method to detect the actual condition of machine. Also, preventive maintenance strategy can be performed on machines if it applies properly [3]. Due to some shortcomings in traditional wear analysis, digitized image vision has become one of the solutions for the problems associated with conventional techniques, especially in case of off-line condition monitoring. Wear mechanism has been classified in several ways by many researchers or industry people. Wear mechanism depends mainly on the two surfaces in contact to each other. Basically, there are two types of wear occur in any machine interaction i.e.

- Mechanical wear (associated with friction, abrasion, impact and fatigue)
- Chemical wear (it attacks the surface by reactive compounds and subsequent removal of the products of reaction by mechanical action)

The maintenance strategy based on monitoring of machinery can be elucidated in various ways but the essential element has been indicated in Figure2.

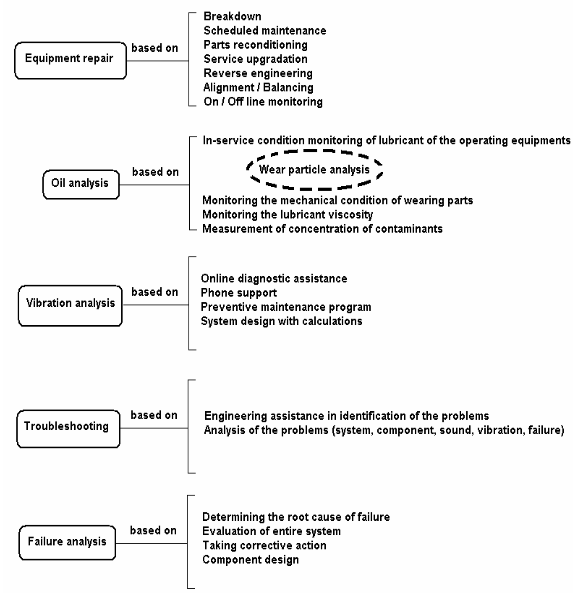


Figure 2: Strategic actions of maintenance based on condition monitoring of machines.

It is a quite well known phenomenon that lubrication is one of the best modes of detection of wear amongst other techniques, but wear particle distributions may be characterized based on the features such as;

- material
- size
- shape
- concentration

The probable damages may occur in gearbox of any industrial machineries, which is shown in Figure3. Wear particles can be simplified as normal particles, fatigue particles, sliding particles, characteristic particlesatrunning in condition, red oxides, black oxides, cutting particles, ball particles, wear polymerides, particles from corrosive wear, impurities, non-ferrous particles, and etc. [4].

3. Wear Measurement Techniques

Ferrography techniques have been found as one of the suitable measurement techniques of wear debris. It may provide the sufficient characteristics of particles, so that the operating wear modes within machines may be determined. It can allow the prediction of imminent behavior of machines. It can be used routinely to monitor the condition and wear of the critical components at higher risk. Generally two typical types of measuring techniques are quite popular like Direct Reading (DR) and Analytical Ferrography. But in the present work, direct reading ferrography has been utilized as the operational mode. With the help of the DR instrument, the density of large particles (D_L) and the density of small particles (D_S) can be measured very easily. On the basis of those parameters, the values for wear particle concentrations and the percentages of large particles can be detected. Figure4 and Figure5 show the DR instrument with its general deposition of particles. By performing quantitative analysis of wear particles, the possible mode of wear generation can be detected. Based on the detection of wear, the further course of action for maintenance of equipments can take place [5].

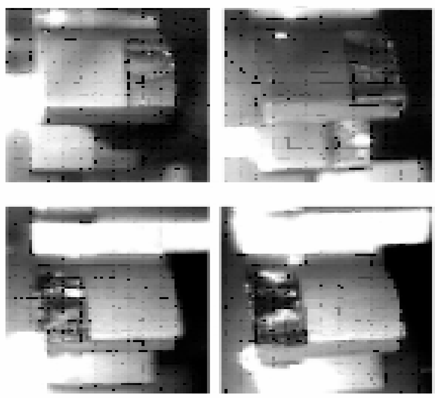


Figure 3: Probable damages in gear tooth.

The number of wear particles can be mathematically deduced by using the relationship,

Severity Index (S.I.) = $(D_L + D_S)(D_L - D_S) = (D_L^2 - D_S^2)$

Where D_L = Number of larger particles, D_S = Number of smaller particles, $D_L + D_S$ = Concentration of solution,

$D_L - D_S$ = Size distribution.

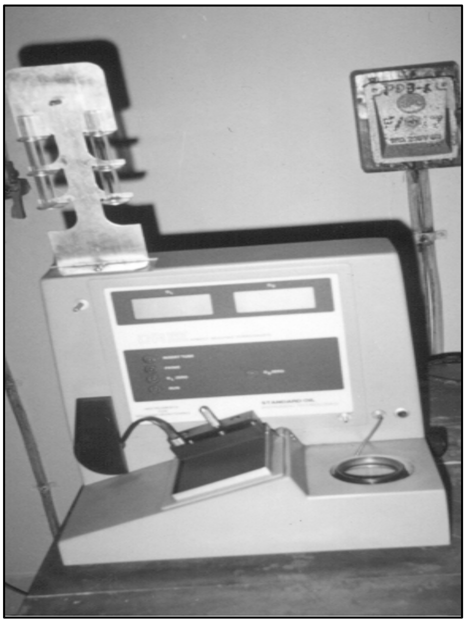


Figure 4: DRIII system for wear separation.

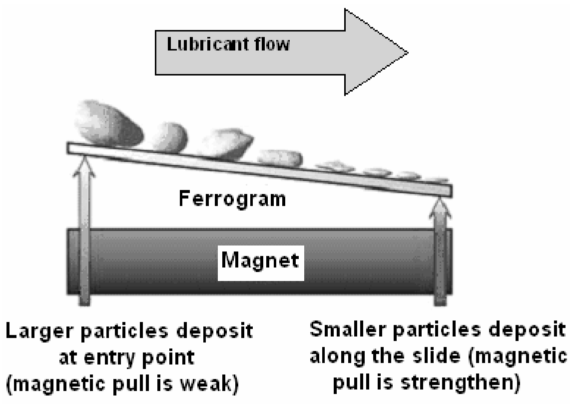


Figure 5: Particles deposition in the ferrograms.

Based on quantitative analysis, qualitative analysis can also be done by using Dual Ferroanalyzer as shown in Figure6. It is basically the ferrogram making instrument, where dual slide makers are available.

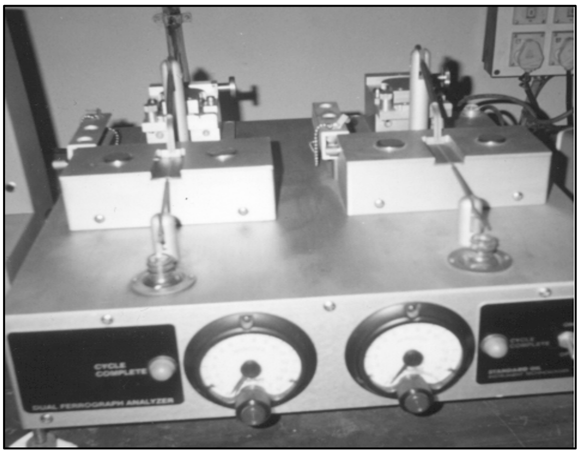


Figure 6 : Dual ferroanalyzer for ferrogram preparation.

It should be used with maximum equipment utilization in wear analysis [5]. For better handling, independent places have been provided where two samples can be prepared concurrently. In the present work, the ferrograms of used oil from gearbox have been prepared by this instrument.

4. Fractal Mathematics Application

Fractal dimension is the technique of quantifying the degree of ruggedness of highly irregular objects. Fractal objects can be found everywhere in the nature like, trees, ferns, clouds, snowflakes, mountains, bacteria, coastlines, and etc. It is very useful in characterizing the roughness of wear debris for machine condition monitoring [6]. Benoit Mandelbrot has proposed this concept in mid 70s. Finding the fractal of any object is quite very important to know about concepts like, self-similarity, chaos and non-integer fractal dimension (FD). Mathematically fractal can be defined as,

$$FD = \lim_{r \to 0} \frac{\ln N}{\ln[\frac{1}{r}]} \quad (1)$$

Where, N = number of self-similar pieces and = magnification factor

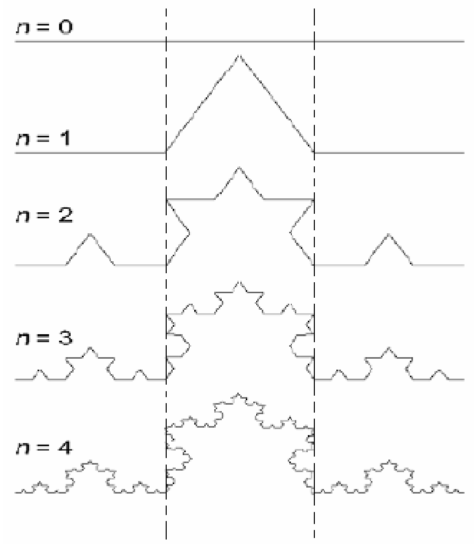


Figure 7: Fractal dimension considering Koch Curve.

In Koch Curve, N = 4, r = 1/3

Hence, FD = (ln 4) / (ln 3) = 1.261

Fractal dimension can also be interpreted by Mandelbrot's method as shown in Figure 8.

Apart from the traditional fractal concepts, EXACT, FAENA, FAST, and etc., algorithms are also quite effective in any imaging techniques. Basically, these kinds of algorithms are computer implementation of Richardson Plot as shown in Figure9.

In this work, FAST algorithm has been applied to minimize calculation hazards [6]. In this algorithm, the step size can be considered as a number of boundary pixels, and the step length may be taken as the Euclidean distance between end points of the predetermined step size. The start and end pixels of the step size are connected by a straight line, and the real particle boundary is approximated by a polygon. After completion of each round, the step lengthens, i.e. the lengths of straight line can be added to each other. The average step length can be calculated by dividing the sum of the step lengths by the number of straight line segments in the polygon.

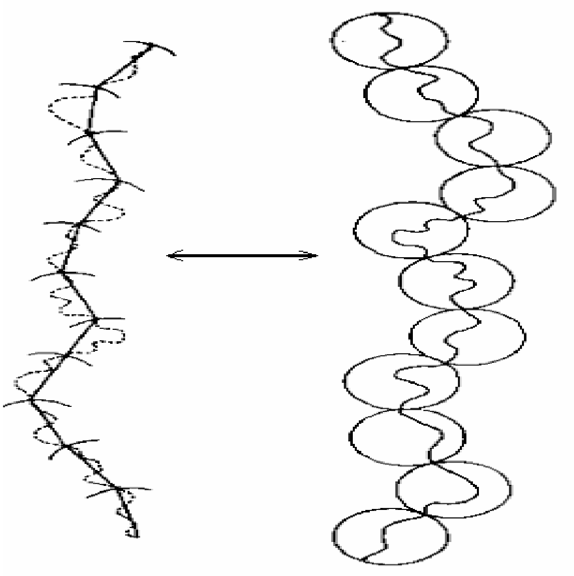


Figure 8: Fractal dimension by Mandelbrot's method.

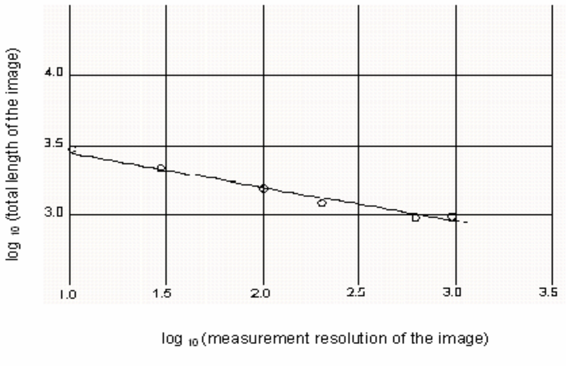


Figure 9: Richardson plot.

The perimeter of the polygon can be calculated by adding the final incomplete step length to the sum of the other step lengths. In this way, the process can be repeated at various step sizes [7]. After that, the perimeter lengths vs. step lengths should be plotted on a log-log scale graphs, and from the plot, fractal dimension can be calculated by using the relationship,

$$FD = 1 - m \tag{2}$$

Where, m = slope of the best fitted line of the log (step length) vs. log (perimeter) plot.

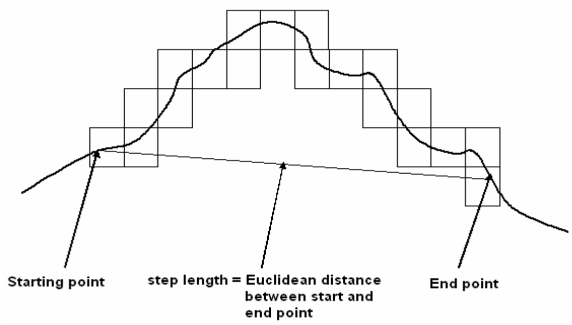


Figure 10: FAST method.

5. Fuzzy Inference System

Fuzzy logic is a logical system, which is an extension of multi-valued logic. But in a broader sense, it is related to the theory of fuzzy sets where the theory relates to classes of objects with non-sharp boundaries in which membership is a matter of degree [8].

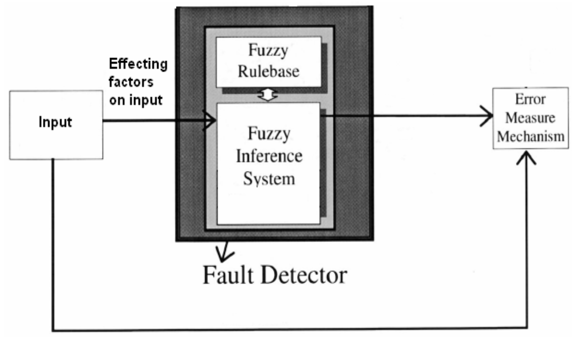


Figure 11: Fuzzy inference structure.

Membership function (MF) in fuzzy inference system is the vital part where a curve that defines how each point in the input space is mapped to a membership value, or degree of membership between ‘0’ and ‘1’ has been graphically interpreted in Figure12.

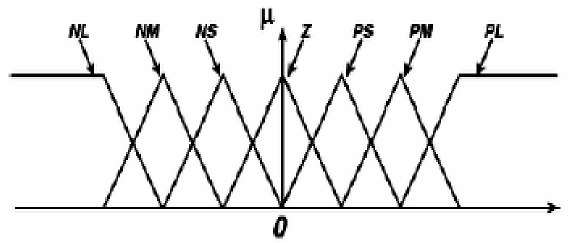


Figure 12: Membership functions for the set of all numbers.

(N = Negative, P = Positive, L = Large, M = Medium, S = Small)

Basically, two types of inference systems have been found for structuring any system, i.e. Mamdani and Sugeno methods. Both techniques are quite efficient to form any inference system, but Mamdani has been used in the present work. In the present work, different rules have been established and have been applied in proper maintenance planning at offline stage of operation.

6. Case Study

The work concentrated mainly on the monitoring strategy of gearbox of rolling mill where condition monitoring through wear analysis has been done. The medium was used oil; and has been collected from the gearbox of cold rolling mill in a reputed industry nearby Kolkata, India. The application of monitoring techniques has a wide range, but in the present work gearbox has been considered as the case study, where the periodic observations took 14-15 days, and depending on that, soft computational strategies have been applied. DRIII ferrograph along with dual ferroanalyzer and color CCD camera mounted on microscope has been utilized in the present work [9]. The entire work has been segmented into different stages, which is shown in Figure13.

The specification of DRIII ferrograph has been considered as indicated by the manual of "Wear Particle Atlas (WPA), Standard Oil Corporation Limited, USA".

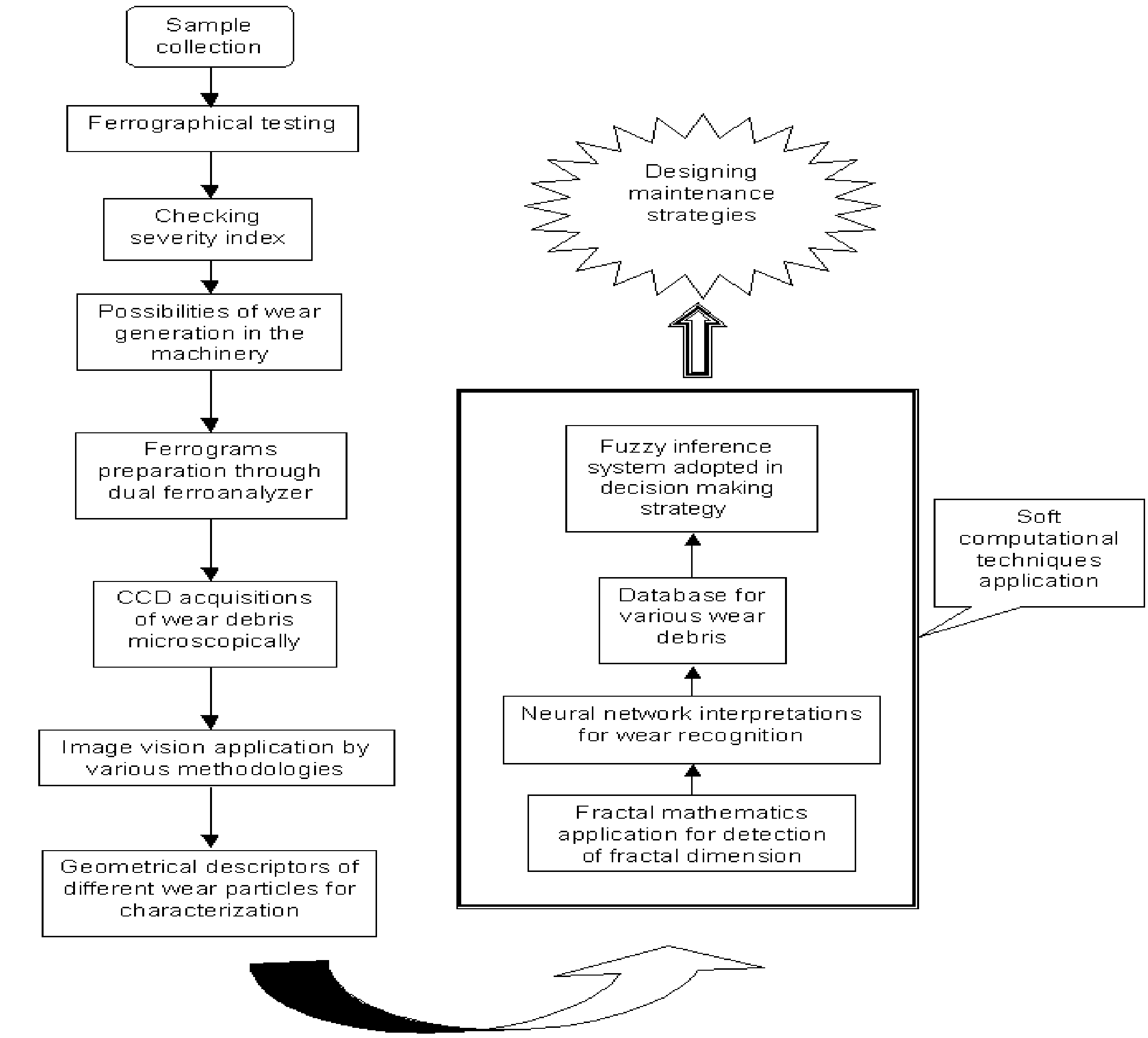


Figure 13: Steps involved in the entire work..

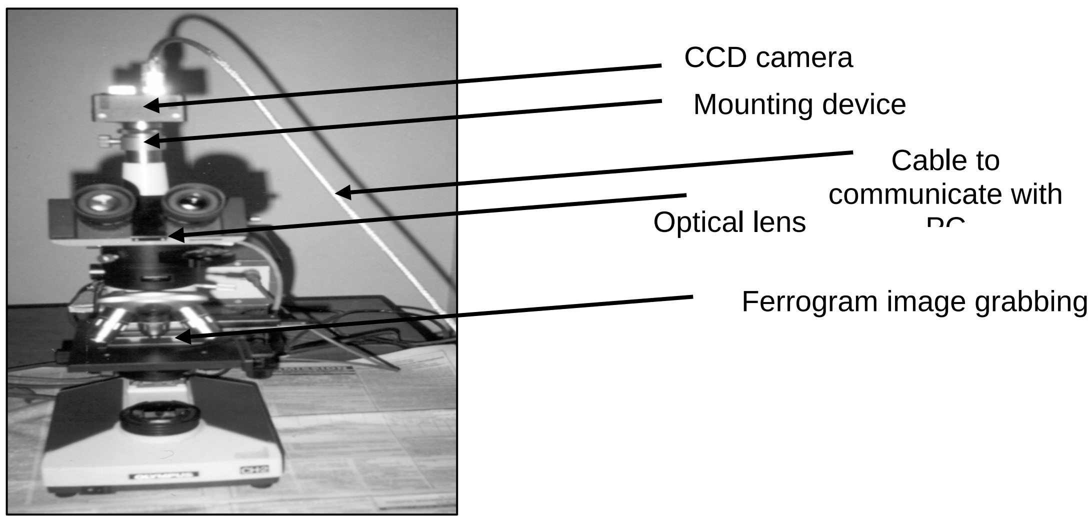


Figure 14: Microscope with CCD camera for image processing of particles.

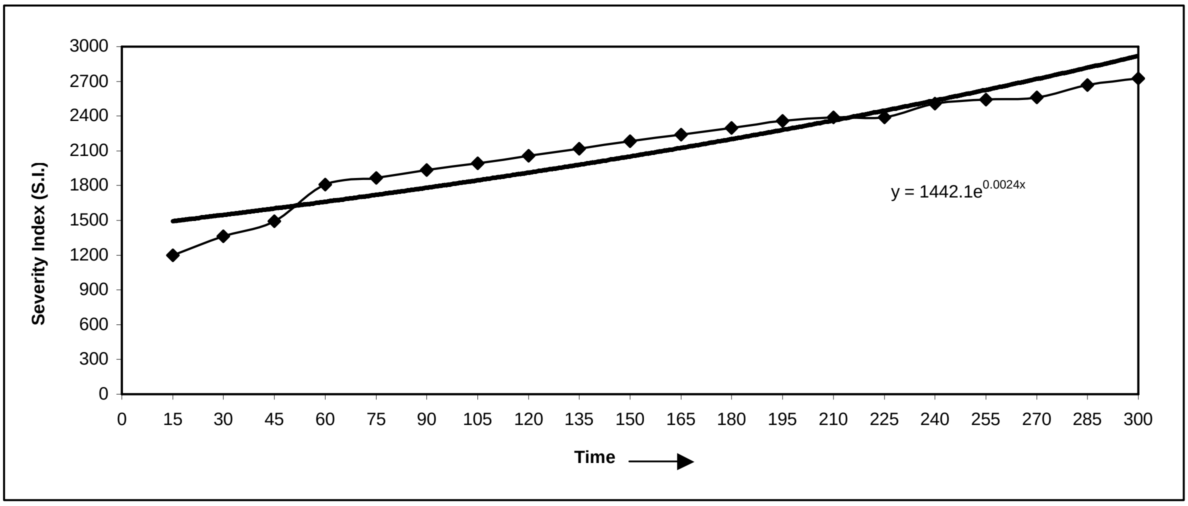


Figure 15: Nature of severity index for gearing system.

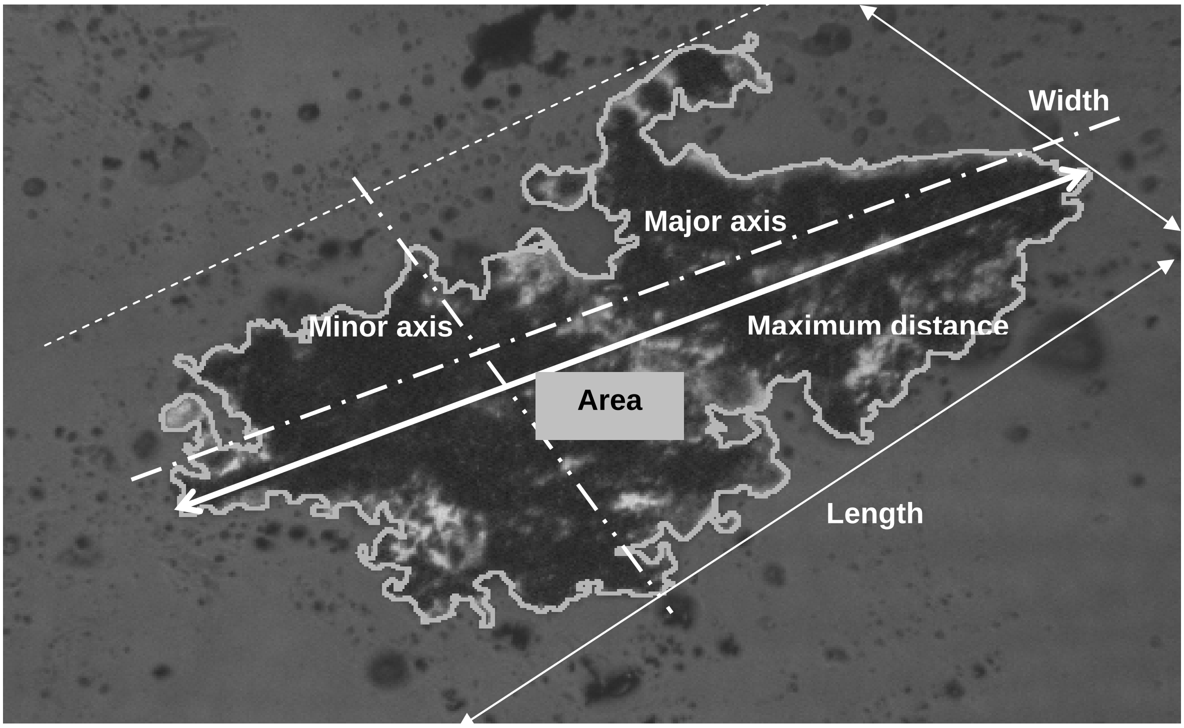


Figure 16: Geometrical parameters projected on wear image.

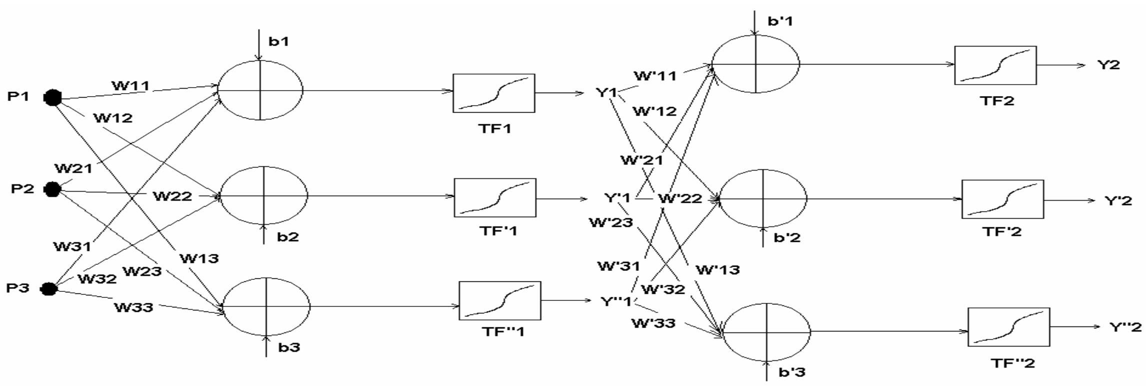


Figure 17: Neural structure for the present work..

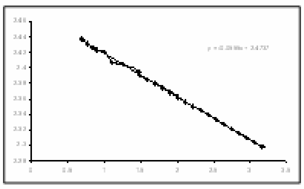
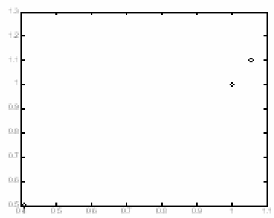
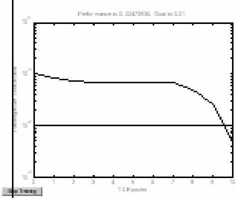
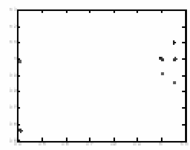
Table 1: Severity index (S.I.) formulation for gearing system of rolling mill.

Length of step (LOS)	log (LOS)	Perimeter (P)	log (P)
6	0.778	270.19	2.431
7	0.845	266.69	2.426
8	0.903	265.38	2.423
10	1	263.17	2.42
13	1.113	255.65	2.407
18	1.255	253.56	2.404
31	1.491	248.64	2.395
26	1.483	246.28	2.391
29	1.588	242.75	2.385
32	1.694	239.23	2.38
36	1.799	235.7	2.374
39	1.904	232.17	2.368
42	2.009	228.64	2.362
45	2.115	225.11	2.356
48	2.22	221.58	2.35
51	2.325	218.05	2.345
54	2.43	214.52	2.339
57	2.535	210.99	2.333
61	2.641	207.47	2.327
64	2.746	203.94	2.321
67	2.851	200.41	2.316
70	2.956	196.88	2.31
73	3.061	193.35	2.304
76	3.167	189.82	2.298

Table 2-a : Wear recognition techniques by fractal dimension Estimation.

Sl. No.	DL	Ds	S.I. = DL2 – DS2
1.	41.60	23.10	1196.95
2.	42.10	20.20	1364.37
3.	41.00	13.70	1493.31
4.	44.00	11.20	1810.56
5.	43.70	6.500	1867.44
6.	44.31	5.280	1935.50
7.	44.92	4.940	1993.40
8.	45.53	4.160	2055.68
9.	46.14	3.380	2117.47
10.	46.75	1.600	2183.00
11.	47.36	1.650	2240.24
12.	47.97	1.580	2298.62
13.	48.58	1.510	2357.74
14.	48.89	1.460	2388.09
15.	48.91	1.410	2390.20
16.	50.11	1.310	2509.29
17.	50.42	1.320	2540.43
18.	50.63	1.250	2561.83
19.	51.65	1.220	2666.23
20.	52.21	1.190	2724.46

Table 2-b: Wear recognition techniques by fractal dimension estimation.

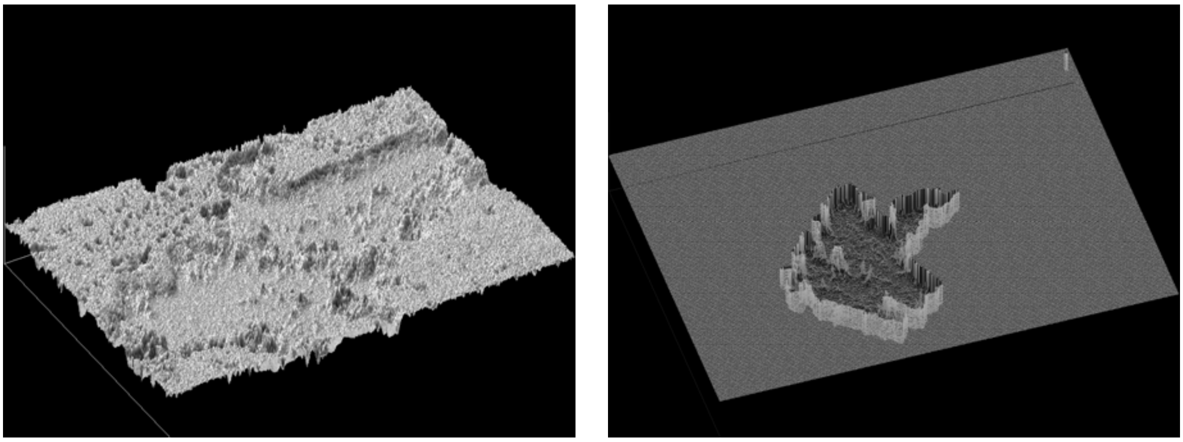
Fractal Dimension estimation	Plot between input vs. target	Training outcomes	Plot between input vs. final output
 Area (A) = 5667.913, Roundness (R) = 1.531, Length (L) = 68.654, Breadth (B) = 82.412, Aspect Ratio (AR) = 0.833, Shape Factor (SF) = 0.653, Dispersion of the Image (DP) = 14.114, FD = 1.0555	 Input vector for the processed image (FD, color, shape) = 1.0555, 0.409, 1 Target vector for network (FD, color, shape) = 1.06, 0.5, 1		 Type of wear = Rubbing Wear

[Note: R = (4 x area) / π .(length)^2, AR = (length / width) of the image, SF = $\log_2(AR)$, DP = $\log_2(\pi LB)$ All dimensions have been taken in μmm.

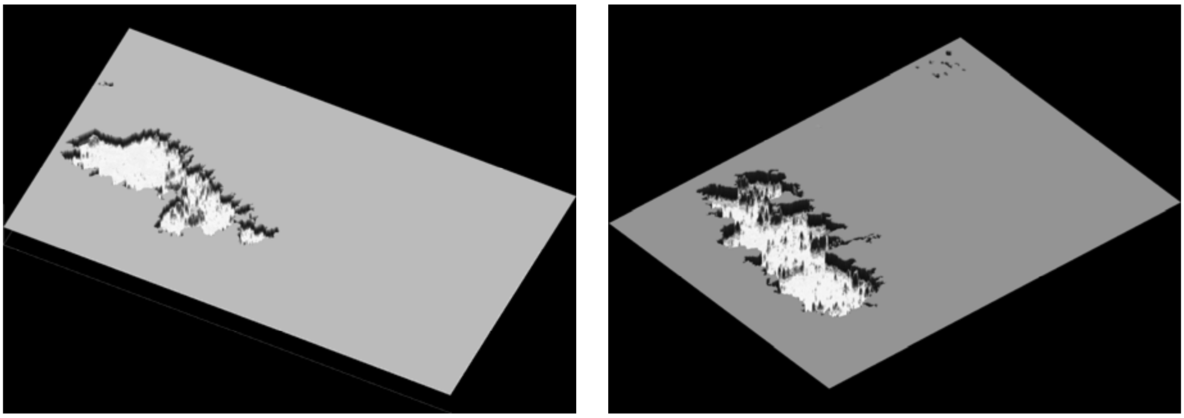
Figure 4, Figure 6, and Figure 14 show the instrumental setup for the experimentation of the present work. After performing the ferrographical testing, the results and severity index (SI) have been checked out properly. In the first stage, the used oil has been collected for testing. In the second stage, the sample has been kept in the ferrograms through ferroanalyzer. In the last stage, the microscopic analysis of wear images has been experimented through color CCD camera [10, 11]. After these stages, the soft computing methodologies have been adopted for explanatory decision making. The entire work has been performed at offline stage to avoid the experimentation hazards, though it can be applied in online stage by building up a knowledgebase system. The severity index has been calculated in the present case of the rolling system (Table 1). Accordingly, the nature of severity has been indicated in Figure15. The actual projection of any wear image has been used in a particular scale (Figure16).

Some of the numerical descriptors have been calculated based on which maintenance strategy has been taken up in this research work [12, 13]. In the present work the backpropagation neural net has been used, which as given in Figure 17.

After the image being recognized, the fuzzy inference system has been applied to reach at a decision making policy of maintenance of the machinery[5].



(a)



(b)

Figure 18: Surface textures of wear images at different angles, a, b.

In fuzzy system, mainly FD, shape and color of the images have been considered as input vector for decision making planning. The basic strategy of the present system has been given in Table-2, where the type of wear recognized as rubbingwear based on which strategy of the maintenance has been considered successfully.

7. Conclusion

The purpose of the present work was to investigate the scope of application domain of soft computing methodologies in automated analysis of various wear mechanisms at the used lubricants of the industrial machineries in offline monitoring process. Mainly, the ferrographical testing of used oil has been performed in the present work and through microscopic view of various wear particles that were generated in machine components where the automated analysis has been performed. But in present work, the usability of fractal mathematics in the particles geometry has been strongly estimated though main emphasis has been given to the neural network. Basically, ANN has been applied for recognition purpose. Amongst other techniques of ANN, back propagation was used to minimize calculation hazards. The proposed methodology is one of the approaches that can be adopted by various organizations, but it can be continued further at online monitoring process by considering the fuzzy concept, too. So that an entire knowledge base system can be prepared. The cost and time factors both can be adjusted by utilizing such kind of system on the field of machine condition monitoring.

Acknowledgement

The authors would like to express thanks to Department of Science and Technology, Ministry of Science and technology, Government of India, New Delhi for funding this project [Ref. No.: III.5 (126)/2001–SERC] and Department of Production Engineering, Jadavpur University, Kolkata for providing the facilities while carrying out this work.

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APPENDIX-A

Pseudo Code for the present work

```
INPUT
        FRACTAL DIMENSION = FD
        COLOUR = C
        SHAPE = S
        MAINTENANCE STRATEGY = MS

IF
        FD = 1.0625
        C = 0.562
        S = 1
THEN
        MS = "Improve the Lubricating Medium"
ELSE
        MS = "Carry on the Regular Maintenance"
```

[This is one example related to the proposed methodology. But this has been applied in different values of the input vectors for various wear particles to get the proper maintenance strategy]