

# Comparative Study on Tree Classifiers for Application to Condition Monitoring of Wind Turbine Blade through Histogram Features Using Vibration Signals: A Data-Mining Approach

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**Abstract:** Wind energy is considered as an alternative renewable energy source due to its low operating cost when compared with other sources. The wind turbine is an essential system used to change kinetic energy into electrical energy. Wind turbine blades, in particular, require a competitive condition inspection approach as it is a significant component of the wind turbine system that costs around 20-25 percent of the total turbine cost. The main objective of this study is to differentiate between various blade faults which affect the wind turbine blade under operating conditions using a machine learning approach through histogram features. In this study, blade bend, hub-blade loose connection, blade erosion, pitch angle twist, and blade cracks were simulated on the blade. This problem is formulated as a machine learning problem which consists of three phases, namely feature extraction, feature selection and feature classification. Histogram features are extracted from vibration signals and feature selection was carried out using the J48 decision tree algorithm. Feature classification was performed using 15 tree classifiers. The results of the machine learning classifiers were compared with respect to their accuracy percentage and a better model is suggested for real-time monitoring of a wind turbine blade.

**Keywords:** Condition monitoring; fault diagnosis; wind turbine blade; machine learning; histogram features; tree classifiers

## 1 Introduction

The 3 axis horizontal axis wind turbine (HAWT) is the most widely recognized design among existing wind energy frameworks, with thousands of MW's of capacity overall mounted every year [1, 2]. Its design technique, to a great extent acknowledged by manufacturers and in addition to scholastic institutions [3]. Wind turbines and their rotor blades ceaselessly increment in size with the purpose of collecting more wind power in higher troposphere elevation. The structural performance of the blades, which is generally of less concern when the blades are small, turns out to be more critical and it fascinates extensive consideration in recent years [4]. There are two types of approaches which are carried out for condition monitoring of wind turbine blade they are conventional and machine learning approach. The conventional

approach is mainly used in applications where the frequency component does not change with respect to time. Rotating machines produce non-stationary signals. Since the frequency components change due to wear and tear, fault discrimination is difficult using an FFT-based traditional approach. Hence, it is not preferred. In the machine learning approach, algorithms have the ability to learn continuously and adapt themselves to varying situations. Researchers often resort to the machine learning approach for fault diagnosis of mechanical systems.

Many studies have been carried out in condition monitoring of wind turbine blades, to mention a few, A model for monitoring wind farm power was conducted by [5] using SCADA data. This study used machine learning algorithms like multi-layer perceptron algorithm (MLP), REP tree, M5P tree, bagging (bootstrapping aggregating) tree and k-nearest neighbor (k-NN) algorithm for comparison of the results. A study on adaptive control of a wind turbine with data mining and swarm intelligence using SCADA data was analyzed by [6]. In this study, a fault simulated for pitch angle twist and classified the fault using particle swarm fuzzy algorithm. [7] have carried out work on classification and detection of wind turbine pitch faults through SCADA data analysis and RIPPER algorithm which yield them 87.05% classification accuracy in pitch angle fault. A study on wavelet transform based stress and time history editing of horizontal axis wind turbine blades was carried out by [8]. With wavelet transform, this method extracts fatigue damage parts from the stress-time history and generates the edited stress-time history with the shorter time length. They used time-correlated fatigue damage (TCFD), Mexican hat wavelet (Mexh), Meyer wavelet (Meyer), Daubechies 30th order (DB30), morlet wavelet (Morl), discrete Meyer wavelet (Dmey) for the classification of crack on the blade. The accuracy they found to be TCFD-89.82%, Morl-80.34%, Meyer-79.76%, Dmey-80.30%, Mexh-79.23% and DB30-80.81% for identifying the crack on blade. Here blade cracks analysis was carried out.

A work on optimization of airfoil profiles for small wind turbines was carried out by [9]. It discussed the development of an automated airfoil shape optimization procedure for small wind turbines, with emphasis on stable performance under highly unstable wind conditions. This study obtained a classification accuracy of 39% using mesh adaptive direct search (MADS) optimization algorithm. [10] made a numerical model for robust shape optimization of wind turbine blades using a 3D geometric modeller. A computational framework for the shape optimization of wind turbine blades was developed for variable operating conditions specified by local wind speed distributions. This study considered the blade design using the simulation process; however, they didn't focus on the faults which affect the performance of a wind turbine. A design and kinetic analysis of the wind turbine blade-hub-tower coupled system was carried out by [11]. In this study, the design was simulated for the 1.5 MW wind turbine and the kinetic analysis was carried out. This study mainly focused on the blade and hub problem. A study on vibration-based experimental damage detection of a small scale wind turbine blade was carried out by [12]. This study is carried out using a 3.5 kW turbine blade by dynamically tested in both its nominal (healthy) condition and for artificially induced damage of varying types and intensities. Their results indicate that statistical-based methods outperform modal-based ones, succeeding in the detection of induced damage, even at low levels.

Numerous studies were carried out using simulation analysis of fault and design analysis of the wind turbine blade; however, only a few studies were carried out experimentally. Machine learning technique was considered for wind turbine blade fault diagnosis; however, its usage was limited in the literature. A very limited set of defects were considered for analysis. This is especially true in the case of a fault diagnosis of the wind turbine blade. Hence, there is a strong need to design a fault diagnosis system that can handle multiple faults in wind turbine blades using a machine learning approach. Many researchers have reported the fault diagnosis of blade faults in wind turbines. However, they considered only one fault or two faults and their classification accuracies were as high as 90%. It is difficult to achieve the same accuracy with multi-class problems with six classes. In the present study, 6 classes were considered

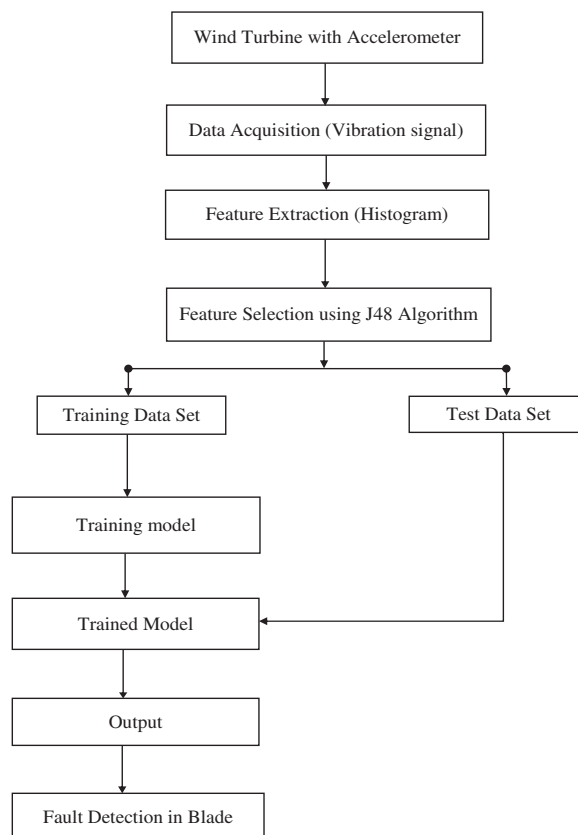
and histogram features with a logistic model tree classifier were used and achieved a classification accuracy of 94.33%. Hence, the contribution of the present study is as follows:

- This study considers five faults (blade crack, erosion, hub-blade loose connection, pitch angle twist, and blade bend) for wind turbine blade fault diagnosis.
- Histogram features with logistic model tree classifiers were used for better classification of wind turbine blades.

The rest of the paper is organized as follows. Section 2 presents the experimental setup and the experimental procedure. In Section 3, feature extraction is explained, followed by feature selection in Section 4. The classifiers used in this study are explained in Section 5. The classification accuracy of the models was discussed and the suggestion of the better model is proposed in Section 6. Conclusions are presented in the final section (Section 7).

## 2 Experimental Studies

Figure 1 shows the methodology of the work done. The main aim of this study is to classify whether the blades are in good condition or in a defective state. If it is defective, then the objective is to identify the type of fault. The experimental setup and experimental procedure are described in the following subsections.



**Figure 1:** Methodology

### 2.1 Experimental Setup

The experiment was carried out on a 50W, 12V variable speed wind turbine (MX-POWER, model: FP-50W-12V). The technical parameters of a wind turbine are given in [Tab. 1](#). The wind turbine was mounted on a fixed steel stand in-front of the open-circuit wind tunnel outlet. The wind tunnel speed ranges from 5 m/s to 15 m/s and acts as a wind source to start the wind turbine. The wind speed was varied continuously in order to simulate the environmental wind condition. The experimental setup is shown in [Fig. 2](#). Piezoelectric type accelerometer was used as a transducer for acquiring vibration signals. It has high-frequency sensitivity for detecting faults. Hence accelerometers are widely used in condition monitoring. In this case, a uniaxial accelerometer of 500 g range, 100 mV/g sensitivity, and resonant frequency around 40 Hz were used. The piezoelectric accelerometer (DYTRAN 3055B1) was mounted on the nacelle near to the wind turbine hub to record the vibration signals using an adhesive mounting technique. It was connected to the DAQ system through a cable. The data acquisition system (DAQ) used was the NI USB 4432 model. The card has five analog input channels with a sampling rate of 102.4-kilo samples per second with 24-bit resolution. The accelerometer is coupled to a signal conditioning unit which consists of an inbuilt charge amplifier and an analog-to-digital converter (ADC). From the ADC, the vibration signal was taken. These vibration signals were used to extract features through the feature extraction technique. One end of the cable is plugged to the accelerometer and the other end to the AIO port of the DAQ system. NI-LabVIEW was used to interface the transducer signal and the system (PC).

**Table 1:** Technical parameters of the wind turbine

Model	FP-50 W-12 V
Rated Power	50 W
Rated Voltage	12 V
Rated Current	8 A
Rated Rotating Rate	850 rpm
Max Power	150 W
Start-up Wind Velocity	2.5 m/s
Cut-in Wind Velocity	3.5 m/s
Cut-out Wind Velocity	15 m/s
Security Wind Velocity	40 m/s
Rated Wind Velocity	12.5 m/s
Engine	Three-phase permanent magnet generator
Rotor Diameter	1050 mm
Blade Material	Carbon fiber reinforced plastics

### 2.2 Experimental Procedure

In the present study, the three-blade variable horizontal axis wind turbine (HAWT) was used. Initially, the wind turbine was considered to be in good condition (free from defects, new setup) and the signals were recorded using an accelerometer. These signals were recorded with the following specifications:

1. Sample length: The sample length was chosen long enough to ensure data consistency; and also the following points were considered. Statistical measures are more meaningful when the number of samples is sufficiently



**Figure 2:** Wind turbine setup

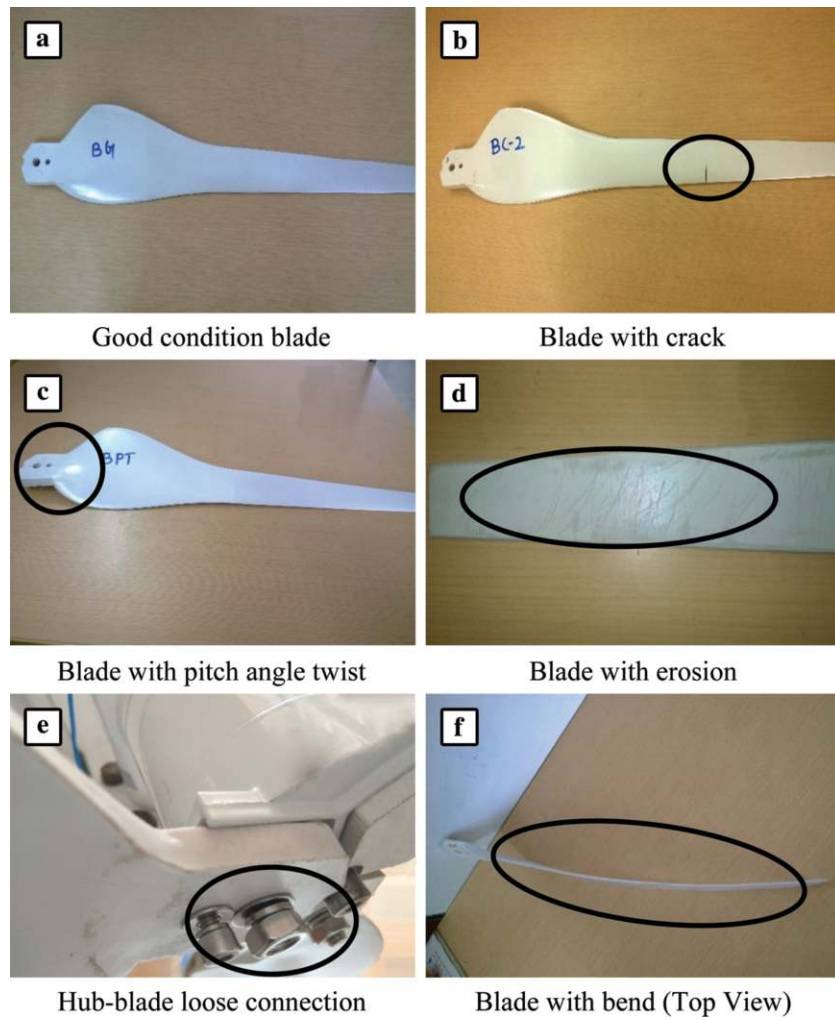
large. On the other hand, as the number of samples increases the computation time increases. To strike a balance, the sample length of 10000 was chosen.

2. Sampling frequency: The sampling frequency should be at least twice the highest frequency contained in the signal as per the Nyquist sampling theorem. By using this theorem sampling frequency was calculated as 12 kHz (12000 Hz).
3. The number of samples: Minimum of 100 (hundred) samples were taken for each condition of the wind turbine blade and the vibration signals were stored in data files.

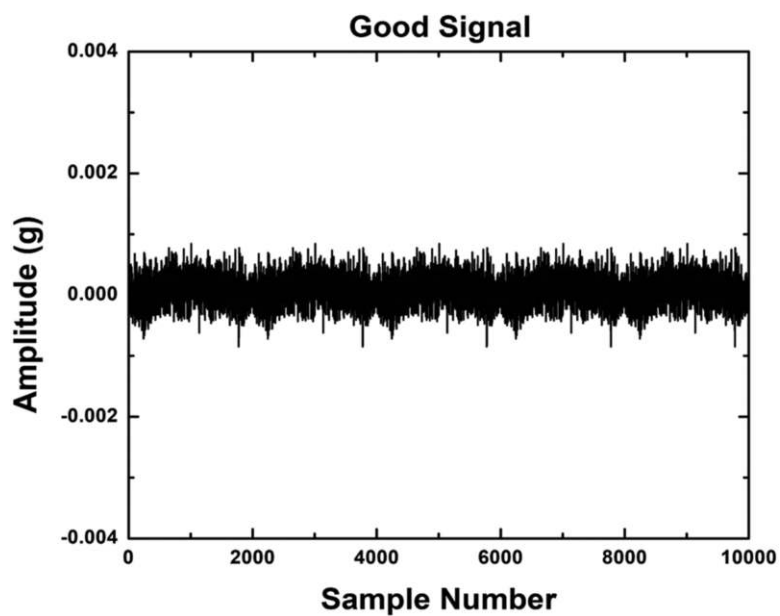
The following faults were simulated one at a time while all other components remain in good condition and the corresponding vibration signals were acquired. Fig. 3 shows the different blade fault conditions which are simulated on the blade.

- a) Blade bend: This fault occurs due to the high-speed wind and complex forces caused by the wind. The blade was made to flap wise bend with  $10^\circ$  angles.
- b) Blade crack: This occurs due to foreign object damage on the blade while it is in operating condition. On blade, a 15 mm crack was made.
- c) Blade erosion: This fault is due to the erosion of the top layer of the blade by the high-speed wind. The smooth surface of the blade was eroded using an emery sheet (320 Cw) to provide an erosion effect on the blade.
- d) Hub-blade loose contact: This fault generally occurs on a wind turbine blade due to an excessive runtime or usage time. The bolt connecting the hub and blade was made loose to obtain this fault.
- e) Blade pitch angle twist: This fault occurs due to the stress on the blade caused by high-speed wind. This makes the pitch get twisted, creating a heavy vibration to the framework. To attain this fault, the blade pitch was twisted about  $12^\circ$  with respect to the normal blade condition.

Figures 4.1 to 4.6 shows the vibration signals which were taken from different conditions of the wind turbine blade. They show the vibration signal plot (amplitude vs sample number) for good condition blade, blade bend, blade erosion, hub-blade loose connection, blade crack, and pitch angle twist respectively.



**Figure 3:** Different blade fault conditions (Considered)



**Figure 4.1:** Good condition signal plot

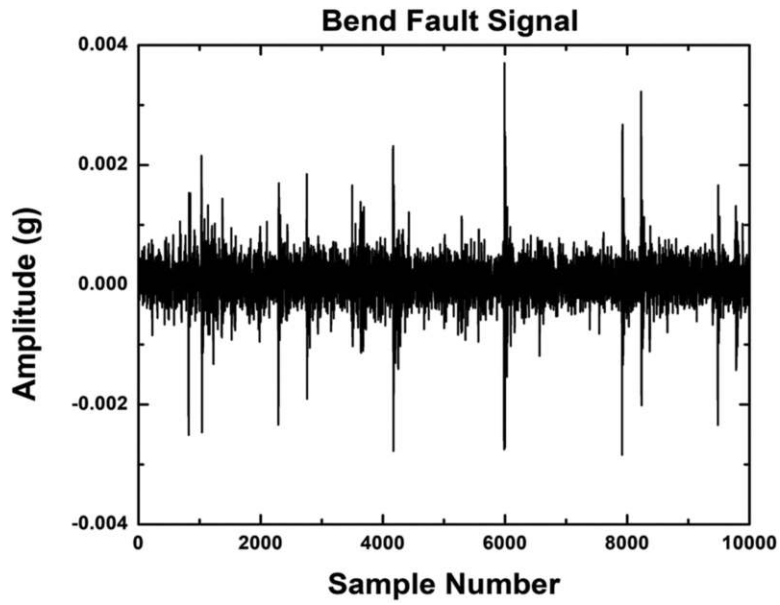


Figure 4.2: Bend fault condition signal plot

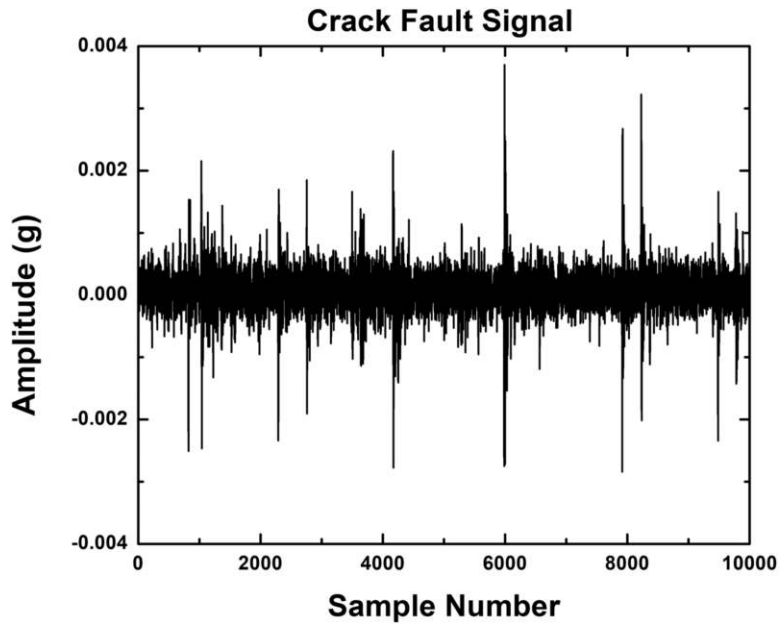


Figure 4.3: Crack fault condition signal plot

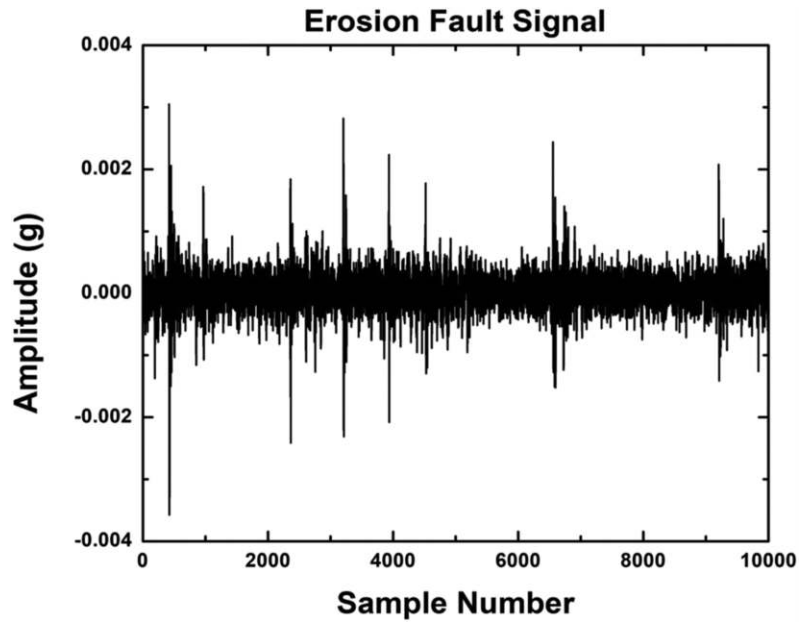


Figure 4.4: Erosion fault condition signal plot

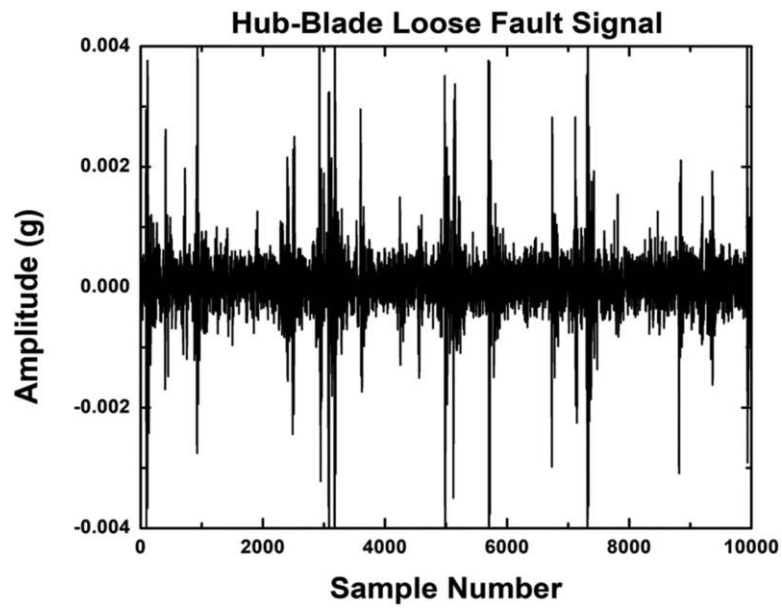
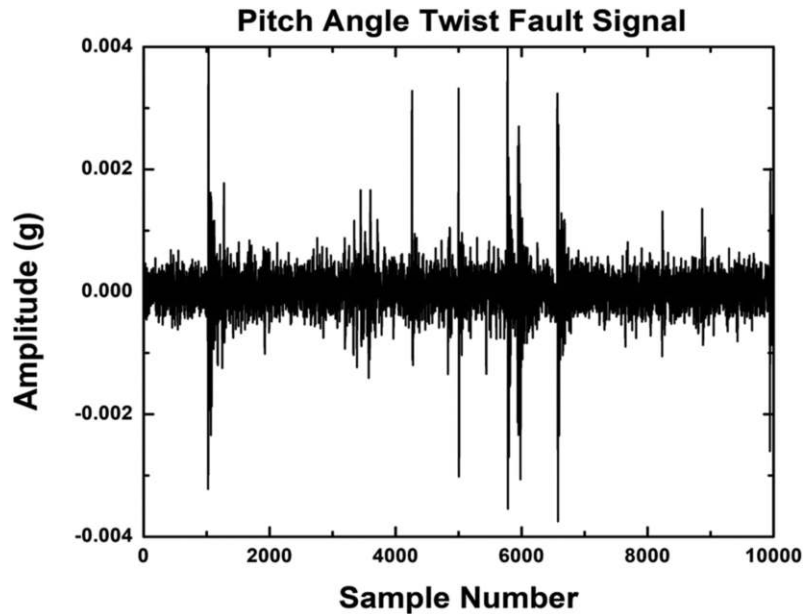


Figure 4.5: Hub-blade loose fault condition signal plot



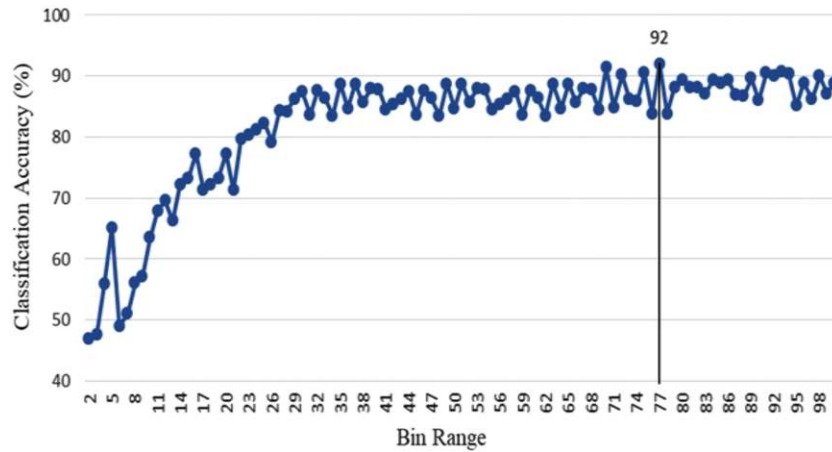


**Figure 4.6:** Pitch angle twist fault condition signal plot

### 3 Feature Extraction

The vibration signals were obtained for good and other faulty conditions of the blades. If the time domain sampled signals are given directly as inputs to a classifier, then the number of samples should be constant. The number of samples obtained is the function of rotational speed. Hence, it cannot be used directly as it functions as the input to the classifier. Hence, a few features must be extracted before the acquired vibration signals, the required features were taken and those features are denoted as histogram features. Here, two main factors are to be taken care of while selecting the bins they are, bin width and bin range. The range of bin must be the lowest of minimum amplitude ( $-0.017988$ ) to the highest of maximum amplitude ( $0.024833$ ) of all the six classes (good, bend, crack, erosion, loose and PAT). The number of bins for the fault diagnosis of the wind turbine blade has been attained by carrying out a sequence of trials using a J48 algorithm with a different number of bins. Initially, the range of each bin is separated into two equivalent portions. That is to say, the number of bins utilized is two. The two histogram features, to be specific,  $X1$  and  $X2$  were extracted and the corresponding classification accuracy was computed using the J48 decision tree algorithm. The approach and methodology of performing the same using the J48 decision tree algorithm are explained in Section 4. The classification accuracies were computed with various numbers of bins from 2, 3, 4, 5, ..., 100 and the corresponding results are shown in Fig. 5.

From Fig. 5, bin size 77 has been chosen since the highest classification accuracy of 92% was found in bin 77. A set of 77 features namely  $X1, X2, \dots, X77$  were extracted from the vibration signals and these are denoted as histogram features. For further study, rather than utilizing vibration signals directly, the histogram features extracted from vibration signals are utilized. The procedure of calculating applicable parameters of the signals that represent the information contained in the signal is called feature extraction. Histogram analysis of vibration signals yields distinctive parameters. All the extracted histogram features,  $X1$  to  $X77$  extracted from the vibration signals may not contain the needed information for classification. The applicable ones are selected using the J48 decision tree algorithm.



**Figure 5:** Classification accuracy vs. bin range

#### 4 J48 Decision Tree Algorithm for Feature Selection

From the extracted features (77), the most contributing features are selected using the feature selection process. For feature selection, the J48 decision tree algorithm is used. The J48 decision tree algorithm is adapted from the C4.5 algorithm in WEKA [13]. It consists of a number of branches, one root, a number of nodes, and a number of leaves. One branch is a chain of nodes from the root to a leaf, and each node involves one attribute. The occurrence of an attribute in a tree provides information about the importance of the associated attribute. A decision tree is a tree-based knowledge representation methodology used to represent classification rules. J48 decision tree algorithm is a widely used one to construct decision trees [14]. The procedure of forming the decision tree and exploiting the same for feature selection is characterized by the following:

1. The set of features available at hand forms the input to the algorithm; the output is the decision tree.
2. The decision tree has leaf nodes, which represent class labels, and other nodes associated with the classes being classified.
3. The branches of the tree represent each possible value of the feature node from which they originate.
4. The decision tree can be used to classify feature vectors by starting at the root of the tree and moving through it right through to a leaf node, which provides a classification of the instance, is identified.
5. At each decision node in the decision tree, one can select the most useful feature for classification using appropriate estimation criteria. The criterion used to identify the best feature invokes the concepts of entropy reduction and information gain.

Information gain measures how well a given attribute separates the training examples according to their target classification. The measure is used to select the candidate among the features at each step while growing the tree. Information gain is the expected reduction in entropy caused by portioning the samples according to this feature. Information gain ( $S, A$ ) of a feature  $A$  relative to a collection of examples  $S$ , is defined as:

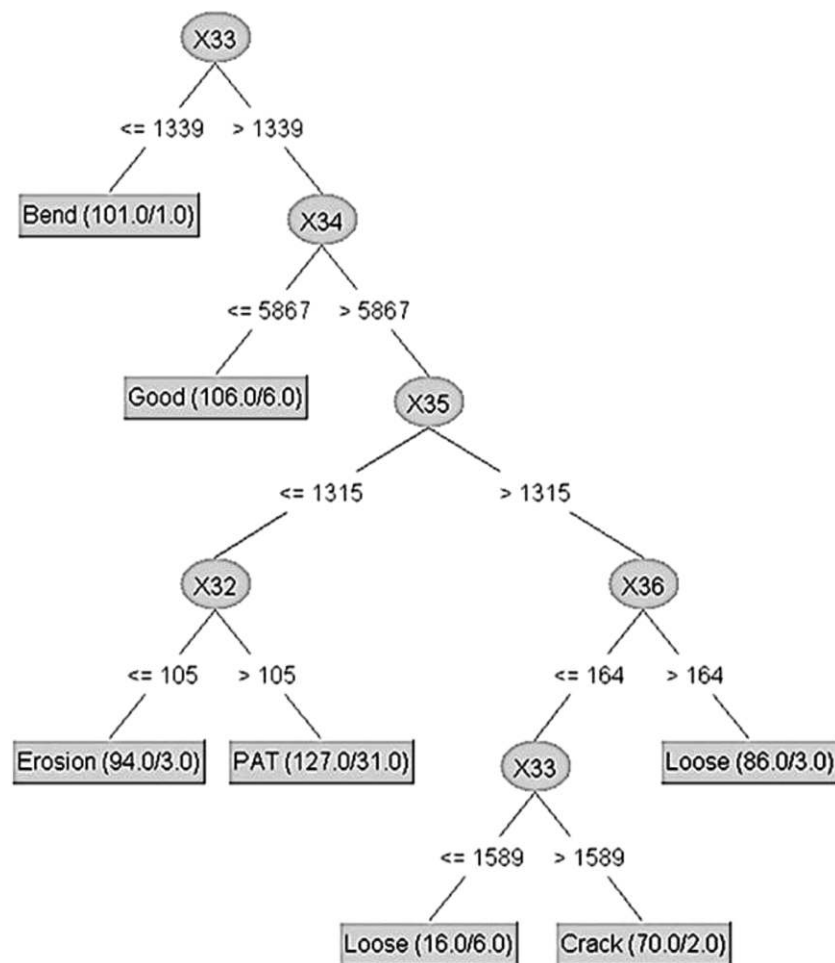
$$Gain(S, A) = Entropy(S) - \sum_{v \in Value(A)} \frac{|S_v|}{|S|} Entropy(S_v) \quad (1)$$

Where  $Value(A)$  is the set of all possible values for attribute  $A$ , and  $S_v$  is the subset of  $S$  for which feature  $A$  has value  $v$ . Note the first term in the equation for gain is just the entropy of the original collection  $S$  and the

second term is the expected value of the entropy after  $S$  is partitioned using feature  $A$ . The expected entropy described by the second term is simply the sum of the entropies of each subset  $S_v$ , weighted by the fraction of samples  $|S_v|/|S|$  that belong to  $S_v$ . Gain ( $S, A$ ) is the expected reduction in entropy caused by knowing the value of feature  $A$ . Entropy is a measure of homogeneity of the set of examples and it is given by

$$Entropy(S) = \sum_{i=1}^c -P_i \log_2 P_i \quad (2)$$

where  $c$  is the number of classes,  $P_i$  is the proportion of  $S$  belonging to class 'i'. The J48 decision tree algorithm has been applied to the problem for the feature selection process. The input to the algorithm is the set of histogram features described above and the output of the decision tree shown in Fig. 6. It clearly shows that the top node is the best node for classification. The other features in the nodes of a decision tree are seen in descending order of significance [15]. It is to be mentioned here that only features that contribute to the classification appear in the decision tree. The features which have less of a discriminating capability can be consciously discarded by deciding on the threshold. This concept is made clear for selecting relevant features. The algorithm identifies the relevant features for the purpose of classification from the given training data set, and thus reduces the domain knowledge required to select



**Figure 6:** J48 Tree classification for feature selection

good features for pattern classification problem [16, 17]. Referring to Fig. 6, one can identify the most dominating features to represent the blade conditions are  $X33$ ,  $X34$ ,  $X35$ ,  $X32$ , and  $X36$ .

## 5 Feature Classification

After feature selection, the selected features ( $X33$ ,  $X34$ ,  $X35$ ,  $X32$ , and  $X36$ ) were given as input to the tree classifiers like best-first tree (BF), decision stump (DS), extra tree (ET), functional trees (FT), hoeffding tree (HT), J48 decision tree (J48), J48 consolidated (J48C), J48 graft (J48G), least absolute deviation regression tree (LAD), logistic model tree (LMT), NB Tree (NBT), random forest (RF), random tree (RT), reduced-error pruning tree (REP) and simple cart classifiers (SCC) [18].

### 5.1 Best-first Tree (BF)

Best-first decision tree learning is one kind of decision tree learning that has almost all properties of standard decision learning. Trees generated by best-first decision tree learning have all properties described in Section 4, however, the only difference is that standard decision tree learning expands nodes in depth-first order, while best-first decision tree learning expands the “best” node first. Standard decision tree learning and best-first decision tree learning generate the same fully-expanded tree for a given data. However, if the number of expansions is specified in advance, the generated trees are different in most cases.

### 5.2 Decision Stump (DS)

A decision stump is a machine learning model comprising of a one-level decision tree. It is also called as weak learners or base learners. It is a decision tree with one inner hub (the root) which is instantly associated with the terminal hubs (its leaves). A decision stump makes a forecast based on the significance of just a distinct input feature. They are additionally called as 1-rules. If the feature is numerical, the tree may be more complex. Decision stumps are often used as components in machine learning ensemble methods such as bagging and boosting.

### 5.3 Extra Tree (ET)

The extra tree algorithm is an ensemble technique that utilizes randomized decision trees. It varies from other randomized decision trees. With the least parameter setting, the algorithm would entirely randomize both the split and the attribute selected at each decision node, yielding a tree completely independent of training data. The extra tree is also called as an extremely randomized tree.

### 5.4 Functional Trees (FT)

The functional tree is the classification tree that could have logistic regression functions at the inner nodes and/or leaves. The algorithm can deal with binary and multi-class target variables, numeric and nominal attributes and missing values. This algorithm is similar to many others, except in the constructive phase. Here a function is built and mapped to new attributes. There are some aspects of this algorithm that should be made explicit. In the next step, a model is built using the constructor function. This is done by using only the examples that fall at this node only. Later, the model is mapped to new attributes. The constructor function should be a classifier or a regressor depending on the type of the problem. In the former, the number of new attributes is equal to the number of classes, in the latter the constructor function is mapped to one new attribute.

### 5.5 Hoeffding Tree (HT)

A hoeffding tree algorithm (HT) is an incremental, anytime decision tree initiation algorithm that is proficient in learning from substantial data streams, assuming that the distribution producing samples does not change over time. A novel paradigm of hoeffding trees was presented in 2000, which forms models that can be verified corresponding to regular decision trees if the data is static and the total

number of samples is sufficiently extensive. Hoeffding trees depend on a direct idea known as the hoeffding bound. It creates natural logic that, given sufficient independent observations, the real mean of a random variable will not change from the predictable mean by more than a definite amount.

### 5.6 J48 Decision Tree (J48)

J48 decision tree algorithm is adapted from the C4.5 algorithm in WEKA. It consists of a number of branches, one root, a number of nodes, and a number of leaves. One branch is a chain of nodes from the root to a leaf, and each node involves one attribute. Furthermore, the technical aspects of the J48 decision tree algorithm are explained in Section 4.

### 5.7 J48 Consolidated (J48C)

J48 Consolidated (J48C) algorithm is also called as consolidated tree construction (CTC) algorithm. It creates a set of subsamples from a training sample and builds a decision tree from each subsample. Instead of building each tree independently, the decision on each split is voted on by all trees. All trees comply with the majority vote and make the same split regardless of their individual vote. The process is repeated until the trees agree to stop growing.

### 5.8 J48 Graft (J48G)

It is an extended version of the J48 decision tree algorithm that considers grafting additional branches onto the tree in a post-processing phase. The grafting process attempts to achieve some of the power of ensemble methods such as bagged and boosted trees while maintaining a single interpretable structure. It identifies regions of the instance space that are either empty or contain only misclassified examples and explores alternative classifications by considering different tests that could have been selected at nodes above the leaf containing the region.

### 5.9 Least Absolute Deviation Regression Tree (LAD)

LAD Tree (LAD) or least absolute deviation regression tree is an alternating decision tree algorithm that can handle multiclass problems based on the LogitBoost algorithm. In LAD Tree, the number of boosting iterations is a parameter that can be tuned to the data at hand and determines the size of the tree constructed.

### 5.10 Logistic Model Tree (LMT)

A logistic model tree essentially comprises a standard decision tree structure with logistic regression tasks at the leaves. As in normal decision trees, a test on one of the qualities is connected with each internal hub. For an identified property with  $k$  values, the hub has  $k$  child hubs, and illustrations are sorted down one of the  $k$  branches relying upon their estimation of the feature. For numeric features, the hub has two child hubs and the test comprises contrasting the characteristic signature to the threshold. Generally, a logistic model tree comprises a tree structure that is comprised of an arrangement of internal or non-terminal hubs  $N$  and an arrangement of leaves or terminal hubs  $T$ . Let  $S$  indicate the entire occurrence in space, spread over by all characteristics that are available in the information. At that point, the tree structure gives a separate section of  $S$  into areas  $S_t$ , and each area is characterized by a leaf in the tree.

$$S = \cup_{t \in T} S_t, \quad S_t \cap S_{t'} = \emptyset \quad \text{for } t \neq t' \quad (3)$$

### 5.11 NB-tree (NBT)

NB-Tree (NBT) is a hybrid between decision trees and Naïve Bayes. It creates a tree with leaves that are Naïve Bayes classifiers for the instances that reach the leaf. When constructing the tree, cross-validation is used to decide whether a node should be split further or a Naïve Bayes model used instead.

### 5.12 Random Forest (RF)

Random forest (RF) is an idea of the general system of random decision forests that are a group learning technique for characterization, regression and other different errands. It works by building a large number of decision trees while execution and yields the class (classification) or mean prognosis (regression) of the individual trees. Random decision forests perfect the decision tree's propensity for overfitting to their training set.

### 5.13 Random Tree (RT)

Random decision tree algorithm (RT) builds numerous decision trees arbitrarily. When building each tree, the algorithm chooses a leftover feature arbitrarily at each hub development without any good role check such as data gain, Gini index, etc. A definite feature such as gender is considered leftover if the same definite feature has not been chosen earlier in a particular decision path preliminary from the origin of the tree to the present hub. Once a definite feature is selected, it is useless to choose it again on the same decision path because every sample in a similar path will have an identical value.

### 5.14 Reduced-error Pruning Tree (REP)

REP tree (REP) or reduced-error pruning tree builds a decision or regression tree using information gain or variance reduction and prunes it using reduced-error pruning. For optimized speed, it only sorts values for numeric attributes. It deals with missing values by splitting instances into pieces, as C4.5 does. One can set the minimum number of instances per leaf, maximum tree depth (useful when boosting trees), the minimum proportion of training set variance for a split (numeric classes only), and a number of folds for pruning.

### 5.15 Simple Cart Classifiers (SCC)

Simple cart classifier (SCC) is a decision tree learner for classification that employs the minimal cost-complexity pruning strategy. Though named after the CART (classification and regression tree) learner that pioneered this strategy, however, the similarity ends here where it provides none of CART's other features. One can set the minimum number of instances per leaf, the percentage of training data used to construct the tree, and the number of cross-validation folds used in the pruning procedure.

## 6 Results and Discussion

The vibration signals were noted for good condition and other fault conditions of the blade using a data acquisition system. Totally 600 samples were collected; out of which, 100 samples were from a good condition blade. For different faults such as blade bend, erosion, blade crack, hub-blade loose connection, pitch angle twist, 100 samples from each condition were noted. J48 decision tree algorithm was used to select the best-contributing features from histogram features. From bin 77, X33, X34, X35, X36, and X32 were chosen as the best contributing features [19]. From Fig. 6, the selected features were given as the input to tree classifiers like a best-first tree (BF), decision stump (DS), extra tree (ET), functional trees (FT), hoeffding tree (HT), J48 decision tree (J48), J48 consolidated (J48C), J48 graft (J48G), least absolute deviation regression tree (LAD), logistic model tree (LMT), NB Tree (NBT), random forest (RF), random tree (RT), reduced-error pruning tree (REP) and simple cart classifiers (SCC). The classification accuracy of different classifiers with their computational time was presented in Tab. 2. The objective of the study is to find, the better the classifier. Amongst the considered classifiers, one can clearly note (from Tab. 2), LMT classifier performs better, compared to other classifiers. This decision was made based on high classification accuracy (94.33%) with low computational time (0.27 s). The confusion matrix of the LMT is shown in Tab. 3. In the confusion matrix, the diagonal elements represent the correctly classified instances and the others are misclassified instances. The first row of the confusion matrix, Tab. 3, represents good condition. The first element (the location (1, 1)) represents the number of correctly classified instances belonging to the same [20]. The second element (the location (1, 2))

**Table 2:** Classification accuracy of the classifiers

S.No	Classifiers	Classification Accuracy (%)	Time (s)
1.	BF	92.00	0.75
2.	DS	33.33	0.02
3.	ET	84.17	0.04
4.	FT	92.83	0.72
5.	HT	90.83	0.26
6.	J48	89.83	0.04
7.	J48C	89.17	0.02
8.	J48G	89.67	0.07
9.	LAD	90.17	0.48
<b>10.</b>	<b>LMT</b>	<b>94.33</b>	<b>0.27</b>
11.	NBT	89.67	0.75
12.	RF	93.00	0.48
13.	RT	88.33	0.02
14.	REP	90.33	0.02
15.	SCC	91.00	0.52

**Table 3:** Confusion matrix for LMT

Blade conditions	Good	Bend	Crack	Erosion	Loose	PAT
<b>Good</b>	<b>96</b>	0	0	0	4	0
<b>Bend</b>	0	<b>100</b>	0	0	0	0
<b>Crack</b>	1	0	<b>89</b>	1	4	5
<b>Erosion</b>	0	0	3	<b>95</b>	0	2
<b>Loose</b>	4	0	2	0	<b>94</b>	0
<b>PAT</b>	0	0	4	4	0	<b>92</b>

represents the number of good instances that were incorrectly classified as bend fault condition (bend). The third element (the location (1, 3)) represents the number of good instances that were incorrectly classified as crack fault condition (crack). The fourth element (the location (1, 4)) represents the number of good instances that were incorrectly classified as erosion fault condition (erosion). The fifth element (the location (1, 5)) represents the number of good instances that were incorrectly classified as hub-blade loose fault condition (loose). The sixth element (the location (1, 6)) represents the number of good instances that were incorrectly classified as pitch angle twist fault conditions (pitch twist). Similarly, the second row represents the second condition i.e., bend fault condition. The third row represents the data points for the third condition, i.e., crack fault condition. The fourth row represents the data points for the fourth condition, i.e., erosion fault condition. The fifth row represents the data points for the fifth condition, i.e.,

hub-blade loose fault condition. The sixth row represents the data points for the sixth condition, i.e., pitch angle twist fault condition [21].

From the confusion matrix (Tab. 3), Out of 600 samples, 566 samples are correctly classified (94.33%) and the remaining 34 are misclassified (5.67%). These 34 misclassification instances occurred because these have a similar vibration pattern of the other fault condition. For example, for a crack fault condition, due to high wind velocity, the firmness of the blade fails and the vibration pattern of the crack signals may resemble other faults (erosion, loose and PAT) conditions. Because of this, the classifier fails to differentiate among the faults; hence, more misclassification could have happened. From LMT, the kappa statistics were found to be 0.932. It is used to measure the arrangement of likelihood with the true class. The mean absolute error was found to be 0.032. It is a measure used to measure how close forecasts or predictions are the ultimate results. The root means a square error was found to be 0.1187. It is a quadratic scoring rule which processes the average size of the error. The time taken to build the model is about 0.27 s; hence, this can be used in real-time for the fault detection on the wind turbine blade. The detailed class-wise accuracy is shown in Tab. 4. The class-wise accuracy is expressed in terms of the true positive rate (TP), false positive rate (FP), precision, recall, and F-Measure [22].

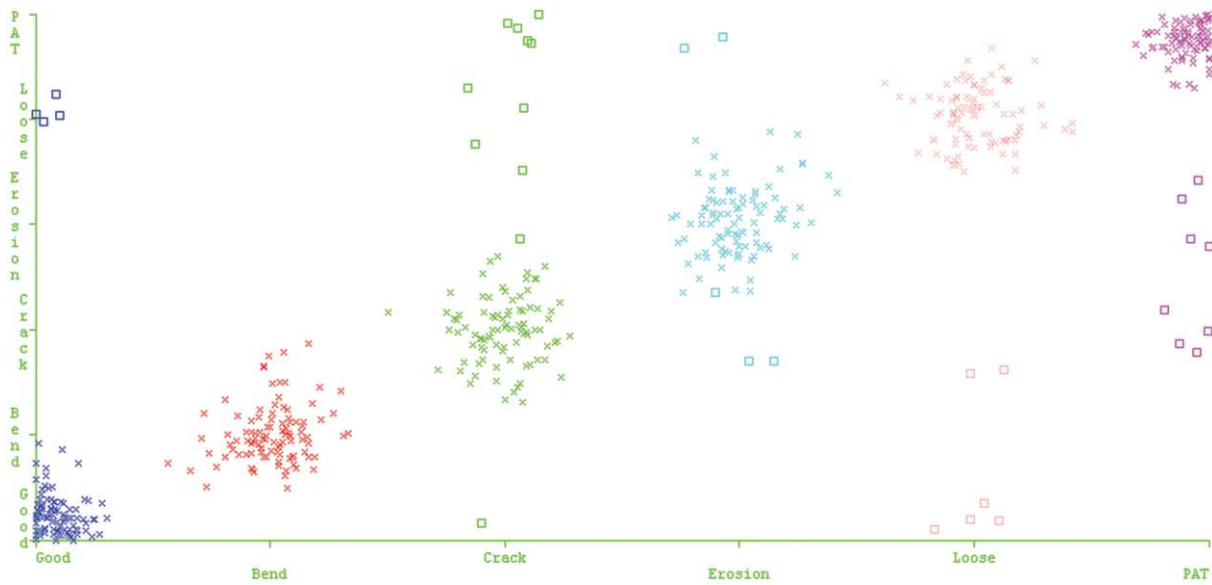
**Table 4:** Class-wise accuracy of the logistic model tree

Class	TP Rate	FP Rate	Precision	Recall	F-Measure
<b>Good</b>	0.960	0.010	0.950	0.960	0.955
<b>Bend</b>	1.000	0.000	1.000	1.000	1.000
<b>Crack</b>	0.890	0.018	0.908	0.890	0.899
<b>Erosion</b>	0.950	0.010	0.950	0.950	0.950
<b>Loose</b>	0.940	0.016	0.922	0.940	0.931
<b>PAT</b>	0.920	0.014	0.929	0.920	0.925

TP is used to predict the ratio of positives which are correctly classified as faults. FP is commonly described as a false alarm in which the result that shows a given fault condition has been achieved when it really has not been achieved [23]. The true positive (TP) rate should be close to 1 and the false positive (FP) rate should be close to 0 to propose the classifier is a better classifier for the problem classification. In LMT, it shows that the TP near to 1 and FP close to 0, hence one can conclude that the classifier built for the specific problem is effective for the fault diagnosis problem. Precision is the probability of retrieved instances that are relevant to the class. That is, it is the ratio of true positive (TP) to the retrieved instances (TP + FP). It is stated as  $TP/(TP + FP)$ . For example, from Tab. 3, for bend condition, the precision value is calculated as  $[1.0/(1.0 + 0) = 1.000]$ . Precision is also called the positive predictive value and can be defined as a measure of exactness or quality. The recall is information retrieval which shows the probability of the faults that are relevant to the classification that is successfully retrieved [24]. That is the ratio of true positive (TP) to the overall instances (TP + FN). False-negative (FN) is considered as a type 2 error in which the instances indicate the misclassification but it is actually correctly classified. It is stated as  $TP/(TP + FN)$ . For example, from Tab. 3, for crack condition, the recall is calculated as  $[0.89/(0.89 + 0.11) = 0.890]$ . Here 0.11 represents the misclassification (11 instances) in crack fault condition from 100 samples (crack condition alone) [25]. A recall is also called as the measure of completeness or quantity. F-measure is defined as the harmonic mean of both recall and precision. That is, this measure is approximately the average of the two (recall and precision) when they



are close, and is more generally the square of the geometric mean divided by the arithmetic mean. The f-measure is expressed as  $2 * (\text{Recall} * \text{Precision}) / (\text{Recall} + \text{Precision})$ . For example, from Tab. 3, for crack condition, the f-measure is calculated as  $[2 * \{(0.89 * 0.89) / (0.89 + 0.89)\} = 0.890]$ . The classifier error chart is shown in Fig. 7. Here the squared dots represent the misclassification and the 'x' denotes the correct classification.



**Figure 7:** Classifier errors (classification vs misclassification)

## 7 Conclusions

The wind turbine is an important structure in extracting wind energy from the accessible wind. This paper displays an algorithm based classification of vibration signals for the evaluation of the wind turbine blade conditions. From the acquired vibration data, fifteen models were developed using data modelling techniques. The models were tested with 10-fold cross-validation. All the classifiers were compared with respect to their types and maximum correctly classified instances. The maximum classification accuracy was found to be 94.33% for the logistic model tree (LMT). The error rate is relatively less and LMT may be considered for the blade fault diagnosis. Hence, the logistic model tree (LMT) can be practically used for the condition monitoring of wind turbine blades to reduce the downtime and to maximize the usage of wind energy. The methodology and algorithm suggested in this paper can be potentially used for any kind of wind turbine blade to diagnose the blade fault with minimal modification.

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