USING VIBRATION SIGNALS AND A RANDOM FOREST CLASSIFIER TO IDENTIFY FAULTS IN ROLLING BEARINGS

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ABSTRACT:
It's critical to identify bearing issues as soon as possible in order to maintain rotary equipment operating smoothly. Our study focuses on the potential applications of feature selection to improve diagnostic prediction models. The Standard Deviation (STD) parameter and the Random Forest (RF) classifier were combined to extract relevant properties from vibration data obtained from bearings operating under various conditions. Three datasets that represented various operational conditions and bearing scenarios were utilised. The positive results of the study indicated that the suggested strategy was not only effective but also long-lasting.
Among the terms are bearing fault, diagnostic, random forest, optimisation technique, and standard deviation.

I.INTRODUCTION:
In recent decades, machine learning (ML) has been extensively involved in fault detection and classification problems.1 However, the robustness of the trained model depends essentially on the quality and the quantity of the input features.2 Therefore the optimization step becomes of tremendous potential accurately determine the perilous conditions.3 Feature selection (FS) arises as an essential step for the effectiveness of ML application,4 the speed of the diagnosis process,5 as well as for the enhancement of
the predictive accuracy.6 Feature selection techniques fall into three main classes.7 The first class is the filter method, which uses statistical methods to rank the features, and then removes the elements under a determined threshold.8 This class provides a fast and efficient selection.6 The second class, called the wrapper class, treats the predictors as the unknown and the predictors' performance as the objective function,8 the problem is reduced to the search algorithm.9 Many subsets are randomly selected and then evaluated by a classifier, and the one with the maximum accuracy is picked.8 The wrapper class is better than the filter class in terms of performance and accuracy. However, for exhaustive searching algorithms,
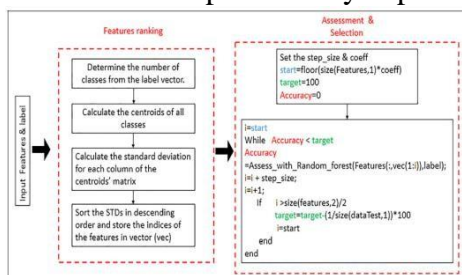it becomes computationally expensive.8,10 The third type

Figure 1. Flowchart of the proposed method.
is the hybrid or embedded class. It is a combination of the advantages of both filter and wrapper classes.11

Many feature selection methods are applied to the bearing fault diagnosis; provided good performances. In Pen˜a et al.,4 the analysis of variance (ANOVA) is used as a filter method to rank the features based on their relevance, then select the subset that yields the best accuracy through cluster validation assessment. This method provides a good classification, but it has some limitations that can be found in any real data. For example, it requires the number of samples from all classes to be equal,12 which, whether by accident or necessity, is not always met. ANOVA requires a tiny variance within samples of the same class to be effi- cient.12 However, in some cases, such as in Imane et al.,13 the data used was collected under variable speed conditions, resulting in sparse samples of the same class. In addition to these constraints, ANOVA necessitates specific knowledge in order to interpret its results.

In Rajeswari et al.,14 they used particle swarm opti- mization (PSO) for the feature selection. In Ma et al.,15 ant colony optimization (ACO) performed the selection step. Both PSO and ACO added strength to the process of bearings' diagnosis by discarding the redundant fea- tures and preserving the relevant ones for the model training. However, PSO suffers from dimensionality issues and the demand for numerous evaluations to attain accurate results.16 While the ACO suffers from local optimization problems.17 In Imane et al.,13 the cultural clan-based algorithm could select the relevant features efficiently within speed variability conditions and enhance classification accuracy. Yet its time complexities can represent a limitation for large data- sets.18 All listed algorithms belong to the wrapper class and ensure high accuracy. However, the trade-off between the high performance and the slow execution is inescapable.2

In this paper, we propose a simple and efficient method for selecting the most relevant features to pave the way for a robust bearing diagnosis process. The idea came from the importance of the centroids to determine the classes. In our method, we aim to select the coordinates (the features) that cause the centroids spacing, and this can be verified by the standard devia- tion parameter, unlike ANOVA our method is based on the geometrical perspective and has no restrictions on the data in terms of quality or quantity. After rank- ing the coordinates of the centroids, random forest classifier (RF) selects the optimal subset that delivers the highest accuracy, to not rely on a distance-based classifier and ensures that the selected features are suit- able for any classifier type.

The rest of the article is organized as follows: The second section describes our proposed method for using the SDT-RF selection method, and the third section represents the datasets used for testing as well as the results obtained. The final section serves as a general conclusion.

The proposed method

The flowchart in Figure 1 elucidates the method suggested for features selection used in the bearing diagnosis process. The following steps outline the pro- posed method.
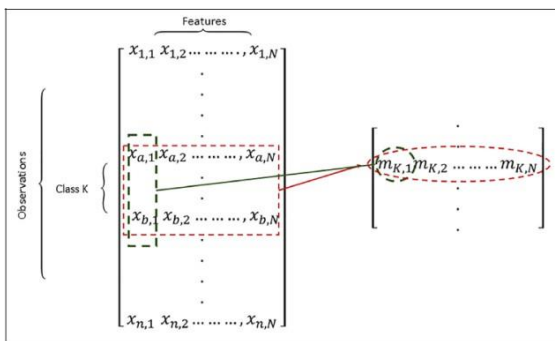

Figure 2. The calculation of the centroids' coordinates.

1.   Determine the number of classes and their corre- sponding number of samples.
2.   Calculate the centroid's coordinates for each class. CK is the centroid of an arbitrary class K, and we calculate it as follows:

$$C_K = \frac{\sum Samples}{size(DataTest)} \qquad (1)$$

Where:

$$Class_K = \begin{bmatrix} x_{1,1} & x_{1,2} & .... & x_{1,N} \\ x_{2,1} & x_{2,2} & .... & x_{2,N} \\ .... & .... & .... & .... \\ .... & .... & .... & .... \\ x_{l,1} & x_{j,2} & .... & x_{l,N} \end{bmatrix}$$

l is the size of samples in class K and N is the number of features.
we expand equation (1) into:

$$C_K = \frac{(x_{1,1}, ..., x_{1,N}) + ... + (x_{l,1}, ..., x_{j,N})}{l}$$

$$C_K = \left(\frac{x_{1,1} + ... + x_{l,1}}{l}, ..., \frac{x_{1,N} + ... + x_{l,N}}{l} \right)$$

$$C_K = \left(\frac{\sum_{j=1}^{l} x_{j,1}}{l}, ..., \frac{\sum_{j=1}^{l} x_{j,N}}{l} \right)$$

Then, the centroid's coordinates are equal to the means of the corresponding class's columns as shown in Figure 2.
3. Compute the standard deviation using equation (2) for each column of the centroids matrix.

$$Centroids = \begin{bmatrix} m_{1,1} & m_{1,2} & .... & m_{1,N} \\ m_{2,1} & m_{2,2} & .... & m_{2,N} \\ .... & .... & .... & .... \\ .... & .... & .... & .... \\ m_{p,1} & m_{p,2} & .... & m_{p,N} \end{bmatrix}$$

Where p is the number of classes,

$$STD_j = \frac{\sqrt{\sum_{i=1}^{p} (m_{i,j} - M_j)^2}}{p} \qquad (2)$$

And,

$$M_j = \frac{\sum_{i=1}^{p} m_{i,j}}{p}$$

We obtain a vector S of N STD value.

$$S = \begin{bmatrix} STD_1 & STD_2 & .... & STD_N \end{bmatrix}$$

4. Sort the vector S in a descending order and save the indices of the corresponding features in vector V .
5. Execute a sequential forward selection on the indices' vector v and assess the performance of the corresponding features with the Random forest classifier. The process starts from 'start'and stops once the accuracy reaches the Target.
● 'start' is the initial index for the sequential selec- tion. It helps to preserve time by considering the indices from 1 to start highly significant features.
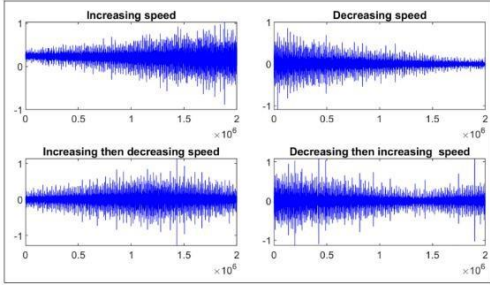
$$start = size(features) \times coef \qquad (3)$$

Figure 3. Vibration signals of inner race defected bearings collected under four speed conditions.

In our application, we set the coef = 5%, assuming that the first 5% are relevant features.

● Target is initially equal to 100%, it is used as a termination criterion in the selection process. If the intended accuracy is not reached with less than half of the features, the Target is adjusted using equation (4) to provide the highest possi- ble accuracy.

$$Target = Target - \left(\frac{1}{size(DataTest)} \times 100 \right) \qquad (4)$$

Experimental part

Datasets

In order to demonstrate the effectiveness of our sug- gested method, we conduct thorough experiments using three different databases The results of these experi- ments will provide valuable insights into the effective- ness of our proposed method and help us determine its potential.

Database 1. The database is called ''Bearing vibration data collected under time-varying rotational speed,'' it contains three bearing health states:

● Healthy
● Inner race defect
● Outer race defect.

Operating under four rotational speed conditions to cover all possible cases of variations:

● Increasing speed
● Decreasing speed
● Increasing then decreasing speed
● Decreasing then increasing speed.

Figure 3 illustrates the data for the vibration signals that were collected while the speed varied continuously. The bearing used is of type ER16K with pitch dia- meter equals 38.52 mm, and nine balls with diameters equal 7.9 mm. The data is collected at a sampling rate of 200,000 Hz for 10 s for each health state under the four operating speed conditions. Three trials are: repeated for each case to ensure authenticity.19

Database 2. MaFaulDa (machinery fault data) is from a spectraQuest's machinery fault simulator (MFS) Alignment-balance-vibration (ABVT). ABVT provides vibration signals along the three axes in addition to the acoustic signal for three faulty bearings with different defective parts (outer track, rolling element, inner track). The table below resumes the sequences for each bear- ing separately in two distinct positions:

● having the bearing between the rotor and the motor (underhang).
● having the rotor between the bearing and the motor (overhang).

The bearing used is of eight balls with diameters equal to 7.145 mm. Sampling rate is 50 kHz, and each sequence takes 5 s while the operating frequency ranges from 737 to 3686 rpm with steps of

approximately 60 rpm. Table 1 lists all masses used for the measure- ments besides the number of trials for each situation.

Table 1. Characteristics of the second database 77.

State	Defect element	Masses (g)	Sequence
Normal	—	—	49
Underhang	Outer track	0	49
		6	48
		20	49
		35	42
	Rolling element	0	49
		6	49
		20	49
		35	37
	Inner track	0	50
		6	49
		20	49
		35	38
Overhang	Outer track	0	49
		6	49
		20	49
		35	41
	Rolling element	0	49
		6	49
		20	49
		35	41
	Inner track	0	49
		6	43
		20	25
		35	20

Database 3. The data is from the Case Western Reserve University Bearing Data Center website.21 It consists of vibration signals collected from the drive end bearing of type 6205-2RS JEM SKF, deep groove ball bearing with an inside diameter of 0.9843 in and an outside diameter of 2.0472 in. The data contains four health state:

- Healthy
- Outer race defect
- Rolling element defect
- Inner race defect.

The defects are of three fault degrees 7, 14, 21 mils.The sampling rate equals 48 kHz for motor speed varies from 1797 to 1730 rpm with steps of approximately 20 rpm. Data preprocessing. The bearing diagnosis procedure consists of three major stages: signal decomposition and feature extraction, feature selection, and classification. we start by processing the Data. For each dataset, we followed these steps:

1. Splitting the waveform of each case into segments based on the calculated period
2. Decomposing each segment using signal decomposition technique.

Table 2. Table of extracted features.

Feature	Equations
Mean square value	$\frac{1}{N}\sum_{i=1}^{N} x_i^2$
Minimum	$Min|x_i|$
Maximum	$Max|x_i|$
RMS	$\sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2}$
Kurtosis	$\frac{N\sum_{i=1}^{N}(x_i-\overline{x})^4}{\left[\sum_{i=1}^{N}(x_i-\overline{x})^2\right]^2}$
Entropy	$E(S) = -\sum S_i^2 log(S_i^2)$
Standard deviation	$\sqrt{\frac{\sum_{i=1}^{N}(x_i-\overline{x})^2}{N}}$
Mean	$\frac{\sum_{i=1}^{N} x_i}{N}$
Variance	$\frac{\sum_{i=1}^{N}(x_i-\overline{x})^2}{N}$
Skewness	$\frac{\sum_{i=1}^{N}(x_i-\overline{x})^3}{(n-1)\sigma^3}$
Crest factor	$\frac{Max|x(n)|}{rms}$
peak2peak	$Max(x) - Min(x)$
RSSQ	$\sqrt{\sum_{i=1}^{N}|x_i|^2}$

3. Computing the features in Table 2 for each mode of the decomposed segment
4. Repeating the steps for all segments of the signal
5. Performing the same process for all cases
6. Preserving the order and number of samples of each state.

The proposed STD-RF selection method is evaluated for its validity through a series of tests. These tests are conducted by using different signal decomposition tech- niques and classification methods.

Moreover, the pro- posed STD-RF selection method is also compared to five strong optimization algorithms.

Results and discussions

On three datasets of rolling bearings collected under different conditions, we apply three signal processing tech- niques: Empirical Wavelet Transform (EWT), Empirical Mode Decomposition (EMD), and Maximal Overlap Discrete Wavelet Packet Transform (MODWPT). For

Table 3. Depicting the performance of the STD-RF algorithm with EWT.

TF	Dataset1 130		Dataset2 520		Dataset3 130	
	Selected features	Execution time (s)	Selected features	Execution time (s)	Selected features	Execution time (s)
1	14	10.20	49	13.44	17	17.71
2	23	42.19	50	12.57	17	12.77
3	14	10.28	49	16.02	17	24.26
4	14	9.95	49	10.70	20	22.49
5	16	17.53	50	13.86	21	26.40
6	14	7.01	49	15.29	20	34.09
7	16	17.53	49	11.30	17	12.83
8	16	12.61	49	12.10	20	29.96
9	19	24.65	49	11.11	23	42.90
10	20	27.06	49	15.80	22	27.39
mean	17	17.90	49	13.21	19	25.08
STD	3.09	—	0.42	—	2.27	—
% of selected features	13.07	—	9.42	—	14.61	—

Table 4. Table depicting the performance of the STD-RF algorithm with EMD.

TF	Dataset1 208		Dataset2 832		Dataset3 208	
	Selected features	Execution time (s)	Selected features	Execution time (s)	Selected features	Execution time (s)
1	7	16.40	132	301.20	13	22.43
2	7	31.82	132	311.70	17	50.80
3	11	25.79	130	283.97	13	19.71
4	10	25.89	129	294.46	14	47.77
5	6	13.93	132	303.46	13	15.84
6	14	46.12	130	281.63	13	18.66
7	12	34.74	132	291.80	13	16.62
8	18	62.31	132	348.93	13	14.74
9	7	15.46	132	338.05	15	32.55
10	12	31.31	135	330.55	13	33.77
mean	11	27.78	132	308.57	14	27.28
STD	3.8	—	1.64	—	1.33	—
% of selected features	5.28	—	15.86	—	6.73	—

the resulting signals, we compute the features listed in Table 2.

Then, we apply the STD-RF selection method to the obtained feature set. We consider the execution time, the number of features opted for, and the obtained accuracy.

We decompose the signal into 10 Amplitude Modulation-Frequency Modulation (AM-FM) modes for the EWT technique.

The number of intrinsic modes functions (IMF) for the EMD technique varies between 12 and 16 for the three databases. We choose 16 as the maximum value to adjust the features matrix without losing any information.

For the three datasets, the MODWPT technique extracts 16 terminal nodes.

Tables 3 to 5 present the features selected by the STD-RF method for three databases processed by EWT, EMD and MODWPT, respectively.

The tables contain the results of 10 simulations using the STD-RF selection method and the execution time for each case. As we can see, our proposed method could reduce the sets of features to less than 15% using the EWT, less than 16% using EMD and less than 10% while using MODWPT and hence help to boost the diagnosis process speed.

From Tables 3 to 5, we observe that the STD-RF's results remain in the same scope despite the signal decomposition technique tool involved in the data pro- cessing. Also, the number of selected features for the 10 simulations affirms the stability of our method in both

Table 5. Table depicting the performance of the STD-RF algorithm with MODWPT.

TF	Dataset1 208		Dataset2 832		Dataset3 208	
	Selected features	Execution time (s)	Selected features	Execution time (s)	Selected features	Execution time (s)
1	21	14.92	83	125.02	20	41.85
2	21	18.03	84	67.85	20	13.10
3	20	8.46	83	49.53	20	10.82
4	20	8.99	83	45.63	20	11.27
5	20	8.25	83	48.69	20	9.30
6	20	7.29	83	50.43	20	12.42
7	20	9.99	83	52.07	21	14.37
8	20	8.07	83	54.84	20	11.31
9	20	8.91	84	64.93	20	27.78
10	20	10.10	83	55.30	21	18.64
mean	20	10.30	83	61.42	20	17.08
STD	0.42	—	0.42	—	0.42	—
% of selected features	9.61	—	9.97	—	9.61	—

quantity and quality terms because of the features' ordering at the beginning of the process.

Selection techniques comparison. We put our method in a comparison with five robust optimization algorithms in bearing diagnosis field. Our method was compared to squirrel search algorithm,21 gray wolf optimization algorithm,22 binary coded differential evolution (BDE), Grasshopper optimization algorithm (GOA),23 and simulated annealing (SA).24

Table 6 demonstrates that the STD-RF selection method exhibits superior performance compared to the other algorithms with respect to both accuracy and the number of selected features. Additionally, the table reveals that for the same dataset, if n simulations yield the same number of selected features, this implies that the n sets are identical, as the vector of indices v is con- sistently ordered irrespective of the initial arrangement of the data. This independence of the output from the initial data's position enhances the system's stability, unlike algorithms where the search procedure is initi- ated randomly and is influenced by the order of the fea- tures, leading to varying feature sets in different simulations. Figure 4 provides a clear representation of the power of our proposed method in feature selection using the first dataset processed by the EWT technique. It reduces number of parameters involved in the classifi- cation process to just 12% without affecting the classi- fication's accuracy.

The accuracies listed in Table 6 were assessed using the RF classifier,we have tested our proposed method using the holdout cross validation and we repeated it 10 times as an explicit 10-fold cross validation to detect any hidden variance between the 10-folds, and this because the k-fold cross validation provides the average of the k simulations without giving an idea about the stability of the system. We spilt the data randomly into 80:20 to have larger amount of data for testing, and we repeated the process for 10 times then we calculated both the average and the STD.

Figures 5 to 7 illustrate clearly the strength of our proposed method in reducing the size of the features set compared to the total features(TF) and the outputs of strong optimization algorithms as the squirrel, gray wolf, BDE, and others, without affecting the accuracy of classification as seen in Table 6.

The accuracy of fault diagnosis can be notably enhanced by utilizing feature ranking.25 The Figure 8 represents a histogram, which illustrates the selected features in the three datasets processed by EWT. These features are arranged in a particular order that corre- sponds to their importance, which is determined based on their standard deviation (STD). The histogram pro- vides a visual depiction of the distribution of the selected features and their relative significance.

Classifiers. To determine the effectiveness of our feature selection method, we perform a thorough evaluation by testing its output with five well-established classifiers. These classifiers include K-Nearest Neighbors, Random Forest, Least-Squares Support Vector Machines, Decision Tree, and Extra-Trees. This evaluation is crucial in verifying the accuracy of the selected features and ensuring that they are capable of providing reliable results when used in the diagnosis of bearings.

Table 7 summarizes the evaluation results of the selected features by the STD-RF method from the three databases processed with the Empirical Wavelet Transform and decomposed into 10 modes.

Table 6. Number of features selected and accuracies obtained by different optimization algorithms.

Simulation	Dataset 1						Dataset 2						Dataset 3					
	Squirrel	Wolf	BDE	GOA	SA	STD-RF	Squirrel	Wolf	BDE	GOA	SA	STD-RF	Squirrel	Wolf	BDE	GOA	SA	STD-RF
1	65	50	124	55	51	16	251	112	398	65	61	49	64	38	110	54	48	17
2	57	56	120	59	53	17	247	125	442	58	57	49	69	45	94	60	48	17
3	54	50	107	58	51	15	236	148	423	61	60	50	77	50	104	52	53	17
4	71	35	122	68	48	20	231	143	415	62	60	49	65	37	75	62	52	20
5	69	42	123	55	57	14	244	108	224	69	67	50	64	44	97	58	54	21
6	59	46	117	59	59	16	244	113	441	65	63	49	66	32	72	52	53	20
7	66	32	72	52	53	20	240	131	469	67	71	49	63	45	113	56	54	17
8	70	44	122	59	60	15	251	182	437	69	67	49	59	58	98	58	51	20
9	68	54	97	62	58	16	210	192	458	60	64	49	70	38	97	56	56	23
10	73	40	126	64	53	21	229	169	248	68	63	49	60	36	95	54	56	22
Mean	65	46	117	60	54	17	238	142	385	64	63	49	66	42	96	56	53	19
Accuracy (%)	98.61	100	100	99.06	99.02	100	99.46	99.78	99.78	99.71	99.67	99.89	99.46	99.78	99.78	99.71	99.67	99.89

Table 7. Classification results of different classifiers using the selected features from the three databases.

| Simulation	Dataset 1					Dataset 2					Dataset 3				
	RF	KNN	LSSVM	ET	DT	RF	KNN	LSSVM	ET	DT	RF	KNN	LSSVM	ET	DT
1	100%	98.95%	100%	99.30%	97.54%	100%	99.20%	99.73%	100%	98.40%	99.64%	99.28%	99.64%	100%	95.35%
2	100%	98.61%	99.65%	100%	98.26%	100%	98.93%	99.73%	100%	98.93%	100%	98.57%	99.25%	100%	95%
3	100%	99.30%	99.30%	100%	96.52%	100%	98.66%	100%	100%	98.66%	100%	98.21%	99.28%	100%	95.71%
4	100%	99.65%	100%	99.30%	98.26%	100%	99.20%	100%	100%	99.46%	100%	98.92%	100%	100%	96.07%
5	99.65%	99.61%	100%	99.65%	97.28%	99.73%	99.20%	100%	100%	98.93%	99.64%	97.85%	99.28%	99.64%	96.07%
6	100%	98.95%	99.65%	100%	99.30%	100%	99.46%	100%	100%	99.73%	100%	98.92%	99.28%	100%	95.35%
7	100%	99.65%	98.95%	99.65%	98.95%	99.73%	99.20%	100%	100%	97.60%	100%	98.21%	100%	100%	97.14%
8	99.65%	99.65%	100%	99.65%	99.30%	100%	99.46%	100%	100%	98.66%	99.64%	97.14%	99.64%	100%	94.64%
9	99.30%	98.61%	99.65%	98.95%	99.30%	99.73%	99.73%	99.73%	99.73%	97.33%	100%	97.85%	100%	100%	96.07%
10	100%	98.95%	100%	99.30%	97.91%	100%	99.73%	99.73%	100%	98.66%	100%	98.57%	99.64%	99.64%	95%
Max	100%	99.65%	100%	100%	99.30%	100%	99.73%	100%	100%	99.73%	100%	99.28%	100%	100%	97.14%
Min	99.30%	98.61%	98.95%	98.65%	96.52%	99.73%	98.66%	99.73%	100%	97.33%	99.64%	97.14%	99.28%	99.64%	94.64%
Mean	99.86%	99.19%	99.69%	99.58%	98.25%	99.91%	99.27%	99.89%	100%	98.63%	99.89%	98.35%	99.60%	99.92%	95.64%
STD	0.2447	0.4306	0.4370	0.3615	0.9702	0.1304	0.3337	0.1394	0	0.7367	0.1739	0.6338	0.3162	0.1518	0.7301
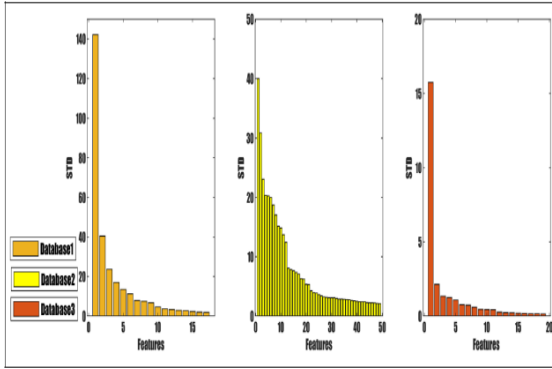
Figure 4. pie chart depicting the percentages of the selected features by different optimization algorithms.
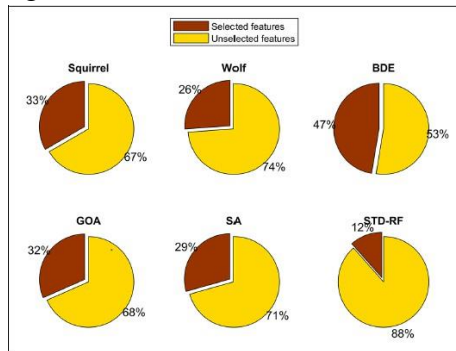

Figure 5. Comparison graph illustrating the number of selected features by different optimization methods for the first dataset.

The obtained accuracies are very promising even with a relatively weak classifier as the Decision tree
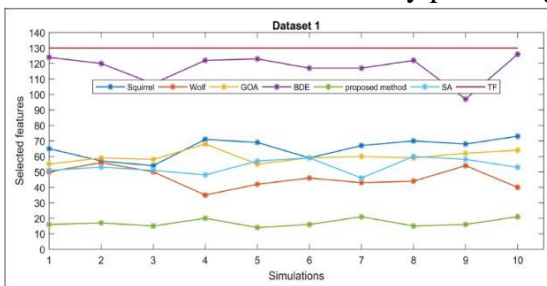

Figure 6. Comparison graph illustrating the number of selected features by different optimization methods for the second dataset.

where the mean accuracies for the three cases are 98.25%, 98.63%, and 95.64% respectively. For KNN, the accuracy approaches 100% while the rest of the classifiers could reach 100%.

Also, we notice the role of our method to retain the system's stability, where the maximum value of the STD is lower than 0.98, which is a low value and deter- mines the robustness of the fault classification.

CONCLUSION

The possible damage that defective bearings might cause has made bearing diagnosis a major focus. However, the caliber of the input features that the classifier uses has a significant impact on the diagnosis's accuracy. The feature selection method is applied in this situation. In this paper, we suggest a feature selection technique based on STD-RF that has a good ability to extract the diagnosis's hazy discriminative characteristics. Using three different databases that were processed using maximal overlap discrete wavelet packet transform, empirical wavelet transform, and empirical mode decomposition, we tested the selection procedure. We evaluated the selected set of parameters using a variety of classifiers, including LSSVM, RF, KNN, and others. The results show that our suggested solution performs well regardless of the classifier and signal processing technique used. The STD-RF method performs better in terms of accuracy, execution time, and the number of features selected when compared to several robust optimization techniques. The findings demonstrate how the STD-RF-based selection approach can manage the problem of time variability and guarantee the stability of the predictive system.

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