[[1]](#footnote-1)

**Differential Geometric Features fusion based Deep Learning Method of Fault Diagnosis**

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**Abstract:** During the operation of mechanical equipment, various types of faults need to be monitored in real time. Some frequency faults cannot be well detected in the time domain, which makes accurate real-time detection of mechanical equipment impossible. To solve this problem, a fault diagnosis method based on DNN fusion of geometric features is proposed. By introducing the geometric features of the raw data, the problem of the time domain detection being inaccurate when the frequency class faults exist in similar amplitudes is solved. The original, slope and curvature data are respectively constructed into an automatic encoder model to fully excavate the implied frequency information of the data. The experimental results of the rolling bearing show that the method proposed in this paper can detect the frequency fault well.

**Key Words:** Fault diagnosis; DNN; Differential geometric feature fusion

1. **Introduction**

At present, mechanical equipment is more and more inclined to large-scale and complicated. Since various parts of the mechanical equipment are closely connected, failure of any part may cause breakdown of the entire mechanical equipment or even led to large industrial accidents, accurate and timely fault diagnosis is a challenging issue [1-8]. Bearings are the core parts of rotating machinery, be used in a wide range of industrial field. Due to the bearing in use process will appear different degree of wear phenomenon, if not timely monitoring of the bearing failure will result in serious losses, and even endanger the lives of the operator. In this regard, research on bearing fault diagnosis has wide attention from experts both in academic and application [2-6, 8-14]. Therefore, bearing fault diagnosis in the actual industrial production process is very necessary. (故障诊断的意义)

In general, the methods of fault diagnosis can be mainly categorized into 3 classes: physical model based method, knowledge based method, and data-driven based method [7]. Since the precise physical model is unavailable, physical model based methods are difficult to adapt to increasingly complex mechanical equipment fault diagnosis. Quantity of prior knowledge is difficult to process which would invalidate the knowledge based fault diagnosis methods. The data-driven techniques are widely applied in industry for process monitoring and fault diagnosis [9–14]. Principal component analysis (PCA), support vector machine (SVM), and artificial neural network (ANN) are the popular data-driven techniques for fault diagnosis [15–22]. Data-driven methods include statistical feature extraction and Neural network method [8-11]. The method based on statistical feature extraction can only detect faults but not diagnose faults. In recent years, due to the rise of Neural network method, Neural network based methods are widely used in the fault diagnosis of complex systems. （介绍现有的故障诊断方法（数据驱动））

Neural network based methods are the most advanced data-driven method for fault diagnosis. However, due to the non-linearity, instability, high latitude and the large amount of noise pollution, the failure characteristics of mechanical equipment make it impossible to accurately diagnose mechanical equipment [12-14]. Some scholars put forward the use of signal processing feature extraction methods combined with machine learning methods for mechanical equipment failure diagnosis. Widodo and Yang extract frequency-domain features as SVM data sources to detect mechanical problems [13-17]. When the number of samples is small and the signal is non-stationary, Yu et al. Propose a method of rolling bearing fault diagnosis using a combination of SVM and EMD methods [10]. Hu et al. extracted the energy of each node of Wavelet Packet Transform (WPT) from the vibration signal as the characteristic parameter of bearing fault diagnosis, which greatly preserved the time-frequency characteristic of the characteristic information. The combination of WPT and SVM Fault diagnosis, improve the accuracy of fault diagnosis [18-21]. Based on the non-stationary characteristics of vibration signals of rolling bearings, Wang et al. Used WPT to de-noise the collected signals and extract the energy characteristics of wavelet bands of each frequency band as the input characteristics of Artificial Neural Network (ANN) Learning classification ability and self-organization ability to bearing fault classification and diagnosis [22-26]. Yang and Tang etc. Proposed a method that combined the expert system with the BP neural network (BPNN), which fully utilized the advantages of the expert system and ANN and successfully detected the bearing failure [27]; Jiang et al. Proposed a method using a combination of high-order cumulants with BPNN. This method uses high-order statistics as the eigenvector to improve the accuracy of BPNN in bearing fault diagnosis [28,29]. However, in these studies, SVM and BPNN have many shortcomings as a shallow learning method: the essence of SVM is a dichotomizer, which has low learning efficiency in many classification and large sample problems, how to choose suitable kernel function and scale parameter often need to experience, SVM method cannot be real-time monitoring and diagnosis, cannot meet the current real-time monitoring of machinery and fault diagnosis requirements; ANN also has some congenital defects: (1) ANN as a shallow neural network, The convergence speed is slow, easily fall into the local optimum, cannot well characterize the signal characteristic information; (2) learning complex non-linear data has the disadvantage of low efficiency and low classification accuracy. In summary, as a shallow learning method, SVM and BPNN have not been able to effectively extract features under high-dimensional non-steady-state data [30]. Deep learning is a promising feature extraction tool and has aroused widespread concern of scholars [21,28-30]. Compared with shallow learning, deep learning can perform well feature extraction and in-depth study on nonlinear big data [31,32]. (分析基于数据驱动的方法，引入深度学习的方法)

Deep learning, as one of the most popular and hot machine learning methods in the world today, has revolutionized artificial intelligence. Depth neural network (DNN) adopts unsupervised layer-by-layer greedy training algorithm and global parameter tuning based on BP algorithm, which can not only avoid local optimal problems, but also solve the restriction of the number of labels and samples. Hinton and Salakhutdinov first proposed the theory of depth learning in 2006. This theory is used to construct Deep Neural Network (DNN), which can form a more abstract high-level representation by combining nonlinear transformations of multiple layers and combining lower-level features, so that a learning system can discover the distribution of data without depending on artificial feature selection Expression of features, and learn complex expression function [33]. Due to its excellent feature extraction capabilities, it quickly attracted the attention of experts in the field of fault classification. Lu et al. used the good feature extraction ability of deep neural network and used it to diagnose the bearing fault successfully solved the problem that the traditional feature extraction method cannot find the unknown type fault timely and effectively [34]; Jia et al. Used deep neural network to detect rolling Shaft bearing health status [35]; Gan et al. Proposed a fault diagnosis method based on the characteristics of bearing faults [36]. Li et al. Addresses a multimodal deep support vector classification (MDSVC)approach, which employs separation-fusion based deep learning in order to perform fault diagnosis tasks for gearboxes [37]. The method is to fuse the data of time domain, frequency domain and wavelet domain. (介绍深度学习在故障诊断中的一些案例)

Since Many of the methods described above performs a full-time domain-to-frequency domain transformation, this method cannot diagnose a single point-in-time data. In other words, this method cannot achieve the purpose of real-time fault diagnosis. To ensure the real-time fault diagnosis can only use the signal of the time domain. However, fault diagnosis based on amplitude information in the time domain presents great problems. Since the bearing data is a vibration signal, there is a frequent zero-crossing value, which makes it impossible to distinguish the fault type based on the amplitude only at these points. At present, these studies about bearing fault diagnosis have not solved the problem that frequency-type faults are difficult to detect in the time domain and therefore cannot guarantee the real-time fault diagnosis.（目前这些研究都没有解决频率类故障在时域检测困难的问题，无法保证故障诊断的实时性)

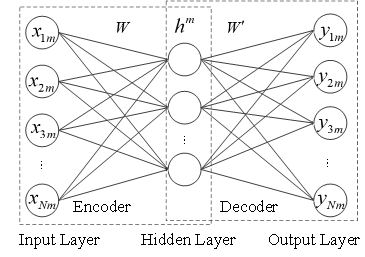
In order to resolve the limitation stated above, this paper developed a differential geometric feature fusion based DNN(DGFFDNN) fault detection method to achieve and improve the accuracy of frequency-type fault diagnosis. State of the art of this research is to design a fusion mechanism by combining differential geometric eigenvectors. By this means, frequency failure can be well detected which is significant to real-time frequency fault diagnosis. The main innovation is to solve the problem of inaccurate time-domain detection when frequency class faults have similar amplitudes and frequent zero crossings by introducing the geometric features of the raw data. The original, slope and curvature data are respectively constructed into an automatic encoder model, so as to fully excavate the implied frequency information of the data. Then, the obtained data features are fused and the feature dimension is increased to make the classification model training more accurate. First calculate the slope and curvature of the raw data that can represent the frequency characteristics of the value. The second step is to construct three DNN networks for training of each feature. The third step is to fuse the obtained features. The final step is to use the already trained network to diagnose the new samples in real time. (介绍本文所提出的方法)

The remainder of this paper is organized as follows: Section 2 review of deep learning based fault diagnosis. In Section 3, a new DGFFDNN fault online diagnosis method is originally developed; In Section 4, the validity of the proposed fault diagnosis method is obtained through experiments and simulation analysis; Sections 5 is the conclusion and future work of this paper. (文章剩余部分组织结构)

1. **Review of deep learning theory**

Deep learning is an unsupervised learning method. By multi-layer nonlinear transformation, low-level features combined to form more abstract high-level representation, making the learning system cannot rely on artificial feature selection, to find the distributed representation of the data, and to learn complex expression functions. Deep learning adopts unsupervised learning to pre-train DNN layer by layer, which helps DNN effectively excavate the fault features in mechanical signals. Then, DNN is fine-tuned by supervised learning to optimize the expression of DNN's fault features and make them have monitoring and diagnostic capabilities. DNNs are pre-trained by stacking Auto Encoders (AE).

Auto-Encoder is a three-layer unsupervised neural network, which is the input layer, hidden layer and output layer. Among them, the input layer and the hidden layer make up the coding network, and the hidden layer and the output layer make up the decoding network. As shown in Fig.1, the input and output of the AE are the same. AE converts input data in a high-dimensional space into coded vectors in a low-dimensional space through a coding network, and coded vectors in a low-dimensional space are reconstructed into raw input data by a decoding network. Since the input signal can be reconstructed at the output layer, the encoded vector becomes a representation of the input data.



**Fig. 1.** The model of Auto-encoder

Given an untagged data set consisting ofobservation features or variables, each observation variable has  samples. the encoding and decoding process of auto-encoder can be expressed as:

 (1)

 (2)

Where  is the activation function for the encoding network, is the weight of the input layer and the hidden layer,  is the bias vector of the encoding network,  is the activation value of the hidden layer, which is the features of input data ; is the activation function of decoding network, is connected to the hidden layer and output layer weights, is the bias vector for the decoding network, is the network output, which is the reconstruction value of input . and is Sigmoid function. The Sigmoid function can be depicted as follows:

 (3)

The essence of training AE is to train and optimize the network parametersand. In order to make the output as close as possible to the input, we need to optimize the network training parameters. Describe the proximity between input and output by minimizing the reconstruction error.The reconstruction error as shown in Equation 4:

 (4)

In training process, gradient descent method is used for AE parameter optimization, the concrete update form of network parameters can be formulated as formula (5) - (6).

 (5)

 (6)

Where is the learning rate, and  can be calculated by BP algorithm.

DNN can be simply seen as a multi-hidden layer neural network in which multiple AE layers are stacked. The bottom-up unsupervised learning method is used to extract features layer-by-layer and fine-tune the entire network with supervised learning methods. So that the DNN can extract the most essential characteristic attribute of some state of the object from the raw data. DNN structure shown in Fig. 2.



**Fig. 2.** The structure of DNN

First, the DNN network is pre-trained by the unsupervised layer-by-layer greedy training algorithm. Given an untagged input data set as the input to the coding network to practice the first automatic encoder, the coded vector is obtained. Training parameter is obtained by setting x as the output of.is then used as the input to the second automatic encoder  and trained on the network parameter  of .  as hidden layer data of  can be seen as a characteristic representation of . This process is repeated to obtain the hidden layer feature of the  automatic encoder  and the corresponding network training parameter.

Second, add a classifier to the top of the DNN network. The DNN pre-training process is completed through unsupervised training layer by layer, and the layers of feature information are extracted. However, DNN at this time does not have the classification function, in order to achieve the output classification function, but also need to add a DNN classifier on the top. In this paper, we use the Softmax classifier as the output layer of DNN. Use feature of the last hidden layer and the labeled data to train the Softmax classifier. BP algorithm is used to update the network parameter of deep learning. The fine-tuning process uses the labeled data to improve the performance of DNN.

1. **Differential geometric feature fusion based DNN fault diagnosis ~~detection~~ method**

There are many frequency-type faults in the rotating mechanical ~~actual~~ system. For the processing of such faults, the main method is Fourier transform~~ed~~ to obtain the frequency domain information and then diagnose fault based on frequency information. ~~processed.~~ Although frequency-type fault ~~it~~ can be ~~is easily detected~~ well recognized in the frequency domain, it is difficult to ~~detect~~ online diagnose in the time domain. To ensure ~~real-time~~ online fault diagnosis ~~detection~~, it is required to diagnose ~~need to be able to effectively detect~~ such faults in the time domain. And frequency feature should also be characterized in time domain. This section first analyzes frequency-type faults and then describes in detail of the required feature extraction and fault diagnosis methods proposed in this paper.

* 1. **Frequency-type fault analysis**

Since the bearing data is a periodic vibration signal, there will be a large amount of zero-crossing data. These zero-crossing data are equal in amplitude, which makes it difficult to discriminate the health of the bearing based only on the amplitude data. Fig. 3.illustrates fault 1 and fault 2 as an example, where blue line represents the ~~is~~ data for fault 1, and red line ~~is data~~ for fault 2. The normal data’s amplitude is expected to be zero. ~~In~~ Point “a” and point “b” ~~points~~ are the zero-crossing points of fault 2 and fault 1, and their amplitudes are 0. ~~At this time,~~ These two zero-cross points cannot be distinguished based simply on the amplitude information. But if slope data is considered ~~ing their slope data~~, we can clearly distinguish these two faults ~~types~~ since their slopes are 1.73 and 3.73, respectively. So the method based on differential geometric feature fusion proposed in this paper can provide an efficient means ~~is essentially~~ to increase the frequency ~~domain~~ information of the data so as ~~in order~~ to maximize the utilization of useful information. Therefore, this paper first calculates the slope and curvature values of the raw data via Eq.(\*)-Eq.(\*\*)~~as characteristics of the frequency domain information.~~

斜率计算公式 (\*)

曲率计算公式 (\*\*)



**Fig.3.** Slope feature describe

It can be seen from Fig. 4.~~The difference between the~~ Fault data 1 and ~~the~~ fault data 2 can not be well separated in the time domain ~~is small~~, so ~~that the~~ diagnosis effect based simply on ~~the time domain~~ amplitude is greatly reduced. On the other hand, and the difference between the two data’s frequency is more obvious ~~in the frequency domain.~~ This makes the diagnostic effect in the frequency domain greatly improved. However, this diagnostic effect is of no practical significance, because real-time diagnosis is the first requirement of ~~in the~~ health monitoring of actual industrial systems, ~~people hope that the real-time performance of the system is high,~~ which can minimize the security risks. The method based on differential geometric feature fusion proposed in this paper is of much significance in the sense of accomplishing accurate and real-time fault diagnosis~~. very practical. This method can obtain higher bearing fault diagnosis accuracy without~~ using Fourier transform ~~and time domain to frequency domain transform~~. This also provides an innovative way of real-time monitoring of equipment health.



**Fig.4.** Comparison between time domain and frequency domain (图中的fault 2去掉)

* 1. **DGFFDNN-based online fault diagnosis ~~online detection~~ method**

The DGFFDNN based online fault diagnosis method is presented in this section. This section is divided into three parts to introduce the algorithm step by step: DNN-based multi-class feature extraction, multi-class feature fusion, fault online diagnosis. The complete fault diagnosis algorithm is as follows:

* + 1. **Multi-modal ~~type~~ feature extraction** (多模态特征抽取)

The first step of DGFFDNN proposed in this paper is to extract multi-modal ~~data~~ feature involved in the data. This article uses a stacking AE ~~Auto Encoders~~ to extract data features. The multi-modal feature extraction algorithm is as follows:

***Step* 1:** obtain data that characterize the differential geometric features of raw data. It can be summarized in Algorithm 1.

|  |
| --- |
| **Algorithm 1** Get data that characterizes the differential geometric features of the raw data. （我个人感觉数据预处理补用公式写，比算法的形式写更好） |
| **Require:**  : Raw vibration signal data with N fault data sets？？？N究竟是什么？与Step2中的N不一致  （把原始数据也列为该函数的输入，方便后续在线用）: Data preprocessing function, with parameters . |
| 1:**function**  2: for n=1:N  calculate the slope of  calculate the curvature of  5:  6:  7: **return**  (需解释U{X,Y}是什么？？) |

***Step* 2:** Training DNN network model.

~~Respectively~~ Reorganize  into a matrix of n rows and m columns:, respectively..Construct observation (observation 指的是什么？ 变量个数还是集合个数？), each observation

has  samples. This can make more adequate ~~efficient~~ use of deep learning feature mining capabilities. ~~Respectively~~ Construct three DNN networks with N hidden layers, and initialize DNN training parameters.

 (7)

公式（7）的大写Hi和公式（11）的小写hi间的关系？？

Among them,**is(Step 2这一部分为什么要加下标1？？，应该是所有层的参数都包含吧？) the weight matrix of raw data, similarly ~~ity~~, ~~~~ is the weight matrix of the slope data, is the weight matrix of the curvature data. For simplicity, in the rese part, only the original data will be used as an example for description later~~, and will not be described again~~. ** is bias vector is the number of DNN hidden layer neurons,  represent raw data set. Network configuration is saved in. ~~ represent raw data set~~. The number of input neurons of DNN is expressed by using (8). (为什么加下标1？？)

 (8)

And the parameters of DNN are initialized by Eq. (9) - (10)

 (9)

 (10)

Apply~~ing~~ unsupervised layer-by-layer feature extraction ~~to datasets~~ by ~~training~~ DNN ~~for~~ parameters training

 （把h2的公式写出来后再省略号） (11)

Layer-by-layer feature extraction as shown in Fig. 2. get the feature of the top .

Build DNN network model of slope and curvature data in the same manner. Repeat the above AE ~~forward~~ encoding process to extract multi-modal feature ~~the characteristic values of the~~ corresponding to original data, slope data, and curvature data, respectively ~~as follows~~:

 (12)

Whereis the features of raw data;is the features of slope data;is the features of curvature data. ~~;~~

Calculate the reconstruction error of the original data, slope data, and curvature data separately according to Eq. ~~uation~~ (13).

 (13)

Then gradient descent method is used for AE parameter optimization, the specific ~~concrete~~ update process ~~form~~ of network parameters can be formulated as ~~formula~~ Eq. (5) - (6). When the reconstruction error reaches a minimum, it means that the trained AE~~-trained~~ parameters can be a good representation of the characteristics of the data., and , ~~respectively, represents the feature values of AE extracted from~~ corresponding to raw data, slope data and curvature data, respectively. Lastly, ~~Then~~ add a softmax classifier to the top layer of the DNN network.

* + 1. **Multi-modal feature fusion（特征融合）**

~~In this paper,~~ Based on original data, slope data and curvature data, respectively, 3 DNN models is established to extract the multi-modal local frequency feature in time domain. As illustrate in Fig. the slope of different fault data may also equal, that is, we can not well classify different faults by simply use slope feature either. Thus, fusing different multi-modal feature to get a new combined feature is necessary. In this paper different feature is fused by stacked form to get new combined feature. By this fusion process, the feature is augmented to a higher dimensional feature, which can integrate the multi-modal feature to capture the local frequency feature in time domain, just as described in Eq.(14).

The features extracted from the above model are recombined to obtain a new feature vector  ~~f~~, as shown in Eq. ~~uation~~ (14).

 (调整了公式（14）和图的位置) (14)

~~the model of DNN which is established by the original, slope and curvature data respectively can fully extract the fault components of the frequency class contained in the fault signal. In order to make the final diagnosis accuracy higher, we must make full use of the trained network to extract the frequency and time domain features of the data. We establish three DNN model to extract the fault feature respectively.~~ ~~The feature fusion process network structure can be shown in Fig.5.~~



**Fig. 5.** Feature fusion network structure

The whole feature fusion process ~~network structure~~ can be shown in Fig.5. The purpose of feature fusion is to recombine the high-level features extracted by these three automatic encoders. The combination of features is as Fig. 5.



**Fig.5.** Stacked Fusion to get new feature vector

~~The features extracted from the above model are recombined to obtain a new feature vector  f, as shown in Eq. uation (14).~~

~~ (14)~~

In the final step, use the fused feature as input and the fault label of each sample as the output to ~~the~~ train ~~ed~~ the Softmax classifier.

~~can be trained with and to classify the recombined fused features. The softmax classifier will give a detailed formula description in the next online diagnostic section.~~

* + 1. **~~Online diagnosis~~**

On-line diagnosis is the use of off-line learned model parameters to identify faults in real-time data collection. In order to accurately use the DNN model to extract the essential characteristics of the health status of mechanical equipment from the input samples, the following steps are required: First, the data of the collected vibration signals should be preprocessed. Secondly, the preprocessed data is used as the DNN model input unsupervised layer pre-training to extract the characteristics of mechanical equipment health status. Finally, based on the finite number of samples of the sample, the entire network is fine-tuned using the BP algorithm to update the entire network parameters. In this way we can carry out an effective diagnosis of the health status of mechanical equipment. Mechanical equipment fault diagnosis is usually divided into two processes: Offline learning and Online diagnosis. The purpose of offline learning is to train a DNN model using the collected historical data. First, the data is preprocessed on historical data, and then the forward training process of DNN is performed. Finally, the DNN network parameters are adjusted in reverse using labels, and the well trained network parameters are saved. On-line diagnosis is to use the well trained parameters and online data to perform corresponding calculations, and then determine whether the data is fault data. If there is a fault, an early warning is issued. If not, the data collection and diagnosis are continued. Usually, DNN for mechanical equipment fault diagnosis steps shown in Fig. 6.



**Fig. 6.** DNN based fault diagnosis

Detailed steps for online diagnosis are as follows:

***Step* 1:** Add a classifier to the top of the three DNN network.

The DNN pre-training process is completed through unsupervised training layer by layer, and the layers of feature information are extracted. Here need to add a DNN classifier on the top. In this paper, we use the Softmax classifier as the output layer of DNN. We use new feature  and the labeled data to train the Softmax classifier. The probability of each type can be calculated by the following hypothetical function:

 (14)

 (15)

Where, is the new feature vector,  is the model parameter of Softmax. The model parameters can also be optimized by the same means to minimize the cost function. The cost function of Softmax classifier can be defined as follows:

 (16)

Where is indicate function.

A softmax classifier is added at the top of DNN, and a limited set of labels  are used for the reverse adjustment of DNN.

 (17)

 (18)

, can be calculated by (14) - (15), is the number of samples. indicates the output of , is the learning rate of the reverse trimming process.

*Step* 2: Fine-tune the parameters.

For the accuracy of feature extraction and output layer classification, the entire DNN training parameters are supervised finely with a finite number of sample tags and a BP algorithm, and the fine tuning process is completed by minimizing the reconstruction error. The update of training parameters through (19) - (20).

 (19)

 (20)

where  represents the actual output value,  is a parameter set generated from the whole network training, , BP algorithm is used to update the network parameter, and  is the learning rate in the process of deep learning. The fine-tuning process uses the labeled data to improve the performance of DNN. Fault Diagnosis Flowchart Based on GFFDNN is shown in Fig. 7.

* + 1. **Online diagnosis**

Step1: 在线数据多模态特征抽取

When online observation at time  , denoted as , is avaiable，(是否用k，x(k)需看前文样本时刻的符号，一致起来即可), use the well trained DNN1 to extract the amplitude feature of the online original data via Eq.(\*)

 (若文中已有F, 可换个函数符号) (\*)

Where function  is used to illustrate, the online amplitude feature is the output of the trained network (Net,Tr) when  is the input of the network.

Then, waiting for the observation at time , once is available, the slope at time  can be firstly computed via Eq.(\*\*)

 （是否用slope(k)需要跟前文曲率数据的表示符号一致） (\*\*)

Where  is the sample interval.

Similar as the manner in Eq.(\*), the slope feature can be extracted by the well trained DNN2 via Eq.(\*\*\*)

 (\*\*\*)

Waiting for the observation at time , once is available, the slope at time  can be firstly computed via Eq.(a)-Eq(b)

 (a)

 （是否用curvature(k)需要跟前文曲率数据的表示符号一致） (b)

Also the curvatue feature can be extracted by the well trained DNN2 via Eq.(c)

 (c)

Step2: 在线数据多模态特征融合

融合 时刻的多模态特征得到扩维之后的融合特征（需翻译成英文）

 （d）

Step 3: online diagnosis

根据Softmax分类器设计的思想，使得概率最大的那一类，即是在线样本 做在线诊断的结果，

分类器的公式 （e）

在线诊断并非绝对实时，而是延迟两个采样时刻，在算法框图上需要突出出来



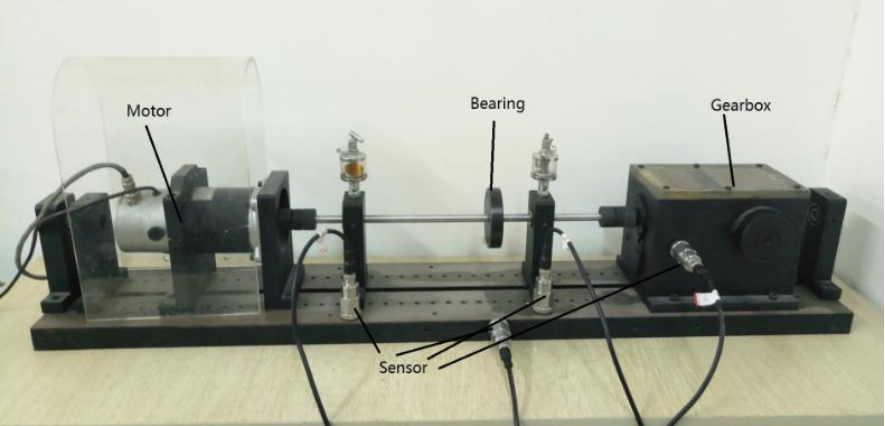
**Fig.7.** Fault Diagnosis Flowchart Based on GFFDNN

1. **Experiment and analysis of bearing faults**

Rolling bearings play a crucial role in rotating machinery, bearing health will directly affect the reliability and stability of the entire system. In this paper, the rolling bearing is used as an experimental platform to verify the effectiveness of the fault diagnosis method for geometric feature fusion. The proposed method is compared with the neural network method without feature fusion.

* 1. **Description of experimental platform**

The experimental data set is the bearing data that collected by Data-driven research team of Henan University built a bearing fault diagnosis test platform. In the bearing fault diagnosis, the vibration signal is the easiest to collect. And the vibration signal is more sensitive to bearing failure. Therefore, vibration signals are widely used in bearing fault diagnosis. In order to further verify the validity of the algorithm, this paper also uses American Western Reserve University Bearing Data Center data as a standard. Acceleration sensor is used in the experiment to collect the vibration signal of motor drive end as experimental data of bearing fault diagnosis. In this experiment, the acceleration sensor is used to collect the motor-driven vibration signal of 0hp, the sampling frequency is 48kHz. There are four types of fault diameter :(1)0.007, (2)0.014, (3)0.021 (4) normal condition. The experimental platform shown in Fig.5.



**Fig. 5.** Experiment platform of rolling bearing

* 1. **Description experimental data**

This article mainly solves the problem that frequency class faults are difficult to detect effectively in the time domain. When such fault signals appear, it is difficult for traditional learning methods to effectively identify different types of faults. This article selects three sets of fault data and a set of normal data. The three sets of fault data are internal fault types, and the load is 0. The difference is that the fault diameter is 0.007, 0.014, and 0.021. The four data types were chosen because these data types have similar amplitude and frequent zero crossings. It makes difficult to effectively distinguish fault types based on time domain signals. The time domain signal is shown in Fig.6.



**Fig. 6.** Observation of raw signals

In addition to using real bearing data, this paper also validates the effectiveness of the proposed algorithm by simulating multiple sets of different types of test data. Among them, there are data with different amplitudes of the same frequency, data with different amplitudes of the same amplitude, and data with different amplitudes and different frequencies, Simulation data generation method is shown as table 2.and the data as shown in Fig. 8, 9, and 10, respectively.

**Tab.2.** Simulation data

|  |  |  |  |
| --- | --- | --- | --- |
| Different experimental scenes | Sampling interval | Signal 1 | Signal 2 |
| different amplitudes with same frequency | 0.1 |  |  |
| different frequency with same amplitude | 0.1 |  |  |
| different amplitudes with different frequencies | 0.1 |  |  |

* 1. **Analysis of results**

Our proposed deep learning based on geometric features is applied to bearing fault diagnosis. There are 4,500 samples under each data type and 4 different data types to characterize the frequency fault types of rotating mechanical systems. In order to reduce the influence of randomness, Experiment repeated 10 times. DNN training uses a stochastic gradient descent method, and the maximum number of iterations of DNN in each layer is 1000, 800, 1000 times respectively. In this paper, DNN's pre-training initialization parameters are shown in Table 1.

**Tab.1.** DNN model parameters

|  |  |  |  |
| --- | --- | --- | --- |
| Training parameter |  |  |  |
| Hidden layers | 6 | 4 | 5 |
| Number of neurons | 500/400/200/100/50/10 | 500/100/50/20/10 | 500/200/100/50/20/10 |
| Max number of epochs | 1000 | 800 | 1000 |
| Learning rate | 0.01 | 0.02 | 0.01 |

In order to verify the effectiveness of the algorithm, different types of simulation data are also verified in this paper. The situation when the signal frequency has same frequency with different amplitudes is shown in Fig.8. On the left is the waveform of the signal. On the right is the diagnostic effect of the proposed algorithm. Red and blue are different fault signals in the waveform diagram. In the diagnostic effect chart, red represents the predicted category, and blue represents the real category.



**Fig.8.** Same frequency with different amplitudes

The situation when the signal same amplitudes with different frequency is shown in Fig.9. On the left is the waveform of the signal. On the right is the diagnostic effect of the proposed algorithm. Red and blue are different fault signals in the waveform diagram. In the diagnostic effect chart, red represents the predicted category, and blue represents the real category. It can be seen that frequency-type faults are difficult to detect in the time domain. Compared to other types of fault monitoring results, detailed data can be found in tab 2.



**Fig.9.** Same amplitudes with different frequency

The situation when the signal different amplitudes with different frequency is shown in Fig.10. On the left is the waveform of the signal. On the right is the diagnostic effect of the proposed algorithm. Red and blue are different fault signals in the waveform diagram. In the diagnostic effect chart, red represents the predicted category, and blue represents the real category.



**Fig.10.** Different amplitudes with different frequency

From the above simulation results, it can be seen that when the amplitude and frequency of the signal are not the same, the diagnostic effect is the best. In addition to the simulation data, this paper also uses the data collected in the test platform built by ourselves to verify. The diagnostic results are shown in Fig. 9. It can be seen that there is a good diagnostic accuracy for bearing data.



**Fig.11.** Detection accuracy of data-driven research team of Henan University data

In addition, we also use the data from the Xi'an University Bearing Data Center to verify this algorithm. The diagnostic results are shown in Figure 12. It can be seen that the proposed algorithm is effective.



**Fig.11.** Detection accuracy of Western Reserve University Bearing Data Center data

Compared with the simulation results without feature fusion, the proposed method is validated. It can be seen from Table 3 that the diagnostic accuracy of the proposed method in frequency class and other faults is higher than that of ordinary neural networks and traditional deep neural networks DNN.

**Tab.3.** Comparison of the accuracy of fault diagnosis

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Data | GFFDNN | DNN | GFFBP | BP |
| Western Reserve University Bearing Center | 98.06 | 89.52 | 87.73 | 81.56 |
| Henan University of Technology Bearing Data | 98.54 | 90.14 | 88.16 | 80.13 |
| Same frequency with different amplitudes | 94.34 | 93.01 | 92.69 | 91.04 |
| Same amplitudes with different frequency | 95.06 | 90.23 | 86.27 | 84.31 |
| Different amplitudes with different frequency | 98.40 | 95.24 | 94.36 | 92.86 |

1. **Conclusion and future work**

In this paper, aiming at the problem that frequency class fault cannot be effectively diagnosed in the time domain, a new DGFFDNN fault online diagnosis method is developed in detail. The main innovation is to solve the problem of difficulty in detecting frequency-type faults in the time domain by introducing the differential geometric characteristics of the original data. When the fault information has similar amplitude and frequent zero-crossing characteristics, the traditional diagnosis method will have the problem of inaccurate diagnosis. In this paper, the original data, slope data and curvature data are respectively constructed into an automatic encoder model to fully excavate the data implied frequency information. Then the obtained data features are merged to increase the feature dimension, so that the fault diagnosis model can be trained more accurately. In addition, this method enables detection of frequency-type faults in the time domain, which will facilitate the real-time detection of the health of the mechanical equipment. The rolling bearing test platform validates the effectiveness of the method.

Large-scale mechanical equipment is getting more and more complicated, and the requirements for fault diagnosis are getting higher and higher. How to implement health monitoring of devices through self-learning algorithms without tag data is a very important research direction in the future

**Reference**

[1] D. H. Zhou, Y. Liu and X. He, "Review on fault classification techniques for closed-loop systems," Acta Automatica Sinica, vol.39, no. 11, pp. 1933-1943,2013.

[2] F. N. Zhou, J. H. Park and Y. J. Liu, "Differential feature based hierarchical PCA fault detection method for dynamic fault," Neurocomputing ,vol.202, pp. 27-35, 2016.

[3] C. Li, RV. Sanchez, G. Zurita, M. Cerrada, D. Cabrera and R. E. Vásquez , "Multimodal deep support vector classification with homologous features and its application to gearbox fault classification," Neurocomputing, vol.168, pp.119-127, 2015.

[4] X. He, Z. Wang, Y. Liu and D. H. Zhou, "Least-Squares Fault Detection and Classification for Networked Sensing Systems Using A Direct State Estimation Approach," in IEEE Transactions on Industrial Informatics, vol. 9, no. 3, pp. 1670-1679, Aug. 2013.

[5] D. Zhao, D. Shen and Y. Q. Wang, "Fault classification and compensation for two-dimensional discrete time systems with sensor faults and time-varying delays, " Int. J. Robust Nonlinear Control, doi: [10.1002/rnc.3742](http://dx.doi.org/10.1002/rnc.3742), 2017.

[6] H. Li and D.Y. Xiao, "Surver on data driven fault classification methods", Control and Decision, vol. 26, no. 1, pp. 1-9+16, 2011.

[7] R. M. An and Y. Gao, "Spacecraft fault classification based on hierarchical neural network," Spacecraft environment engineering, vol. 30, no. 2, pp. 203-208, 2013.

[8] F. N. Zhou , C. L. Wen, Y. B. Leng and Z. G. Chen, "A data-driven fault propagation analysis method", Journal of Chemical Industry and Engineering(China), vol. 61, no. 8, pp. 1993-2001,2010.

[9] H. Q. Ji, X. He and D. H. Zhou, "On the use of reconstruction-based contribution for fault classification, "Journal of Process Control, vol. 40, pp. 24-34, 2016.

[10] D. J. Yu, M. F. Chen, J. S. Cheng and Y. Yang, "A fault classification approach for rotor systems based on empirical mode decomposition method and support vector machines, " Proceedings of the Chinese society for electrical engineering, vol. 26,no. 16, pp. 162-167, 2006.

[11] M. Gan, C. Wang and C. A. Zhu, "Construction of hierarchical classification network based on deep learning and its application in the fault pattern recognition of rolling element bearings" Mechanical Systems and Signal Processing, vol.72-73, pp. 92–104, 2016.

[12] G. F. Bin, J. J. Gao, [X. J. Li](http://www.sciencedirect.com/science/article/pii/S0888327011003207) and [B. S. Dhillon](http://www.sciencedirect.com/science/article/pii/S0888327011003207), "Early fault classification of rotating machinery based on wavelet packets—Empirical mode decomposition feature extraction and neural network," Mechanical Systems and Signal Processing, vol. 27, pp. 696–711,2012.

[13] A. Widodo and BS. Yang, "Support vector machine in machine condition monitoring and fault classification," Mechanical Systems and Signal Processing, vol. 21,no. 6, pp.2560-2574, 2007.

[14] D. Zhao, Z. P. Lin and Y. Q. Wang, "Integrated state/disturbance observers for two-dimensional linear systems," in IET Control Theory & Applications, vol. 9, no. 9, pp. 1373-1383, 2015.

[15] Q. Hu, Z. J. He, Z. S. Zhang and Y. Y. Zi , "Fault classification of rotating machinery based on improved wavelet package transform and SVMs ensemble ," Mechanical Systems and Signal Processing ,vol. 21, no.2, pp. 688–705, 2007.

[16] L. Y. Wang, W. G. Zhao, Y. Liu, "Rolling Bearing Fault Classification Based on Wavelet Packet- Neural Network Characteristic Entropy," Advanced Materials Research, Vols. 108-111, pp. 1075-1079, 2010.

[17] Y. Yang and W. Tang, "Study of remote bearing fault classification based on BP Neural Network combination," 2011 Seventh International Conference on Natural Computation, pp. 618-621,Shanghai, 2011.

[18] L. Jiang, Q. Li, J. Cui and J. Xi, "Rolling bearing fault classification based on higher-order cumulants and BP neural network," The 27th Chinese Control and Decision Conference (2015 CCDC), pp. 2664-2667, Qingdao, 2015.

[19] T. Kuremoto, S. Kimura, K. Kobayashi and M. Obayashi, "Time series forecasting using a deep belief network with restricted Boltzmann machines," Neurocomputing, vol. 137, pp. 47–56, 2014.

[20] S. M. Zhang, F. L. Wang, S. Tan and S. Wang, "A fully automatic onine mode identiflcation method for multi-mode processes," Acta Automatica Sinica, vol. 42, no.1, pp.60-80, 2016.

[21] Jürgen Schmidhuber, "Deep learning in neural networks: An overview," Neural Networks, vol. 61, pp. 85–117, 2015.

[22] G. E. Hinton and R. R. Salakhutdinov, "Reducing the Dimensionality of Data with Neural Networks," Science, vol.313, pp. 504-507, 2006.

[23] H. Ze, A. Senior and M. Schuster, "Statistical parametric speech synthesis using deep neural networks," 2013 IEEE International Conference on Acoustics, Speech and Signal Processing, pp. 7962-7966, Vancouver, BC, 2013.

[24] B. Song, S. Tan and H. B. Shi, "Key principal components with recursive local outlier factor for multimode chemical process monitoring," Journal of Process Control, vol.47,pp.136–149, 2016.

[25] L. P. Zhao, C. H. Zhao and F. R. Gao, "Inter-batch-evolution-traced process monitoring based on inter-batch mode partition for multiphase batch processes," Chemometrics and Intelligent Laboratory Systems, vol.138, pp.178–192, 2014.

[26] Y. W. Zhang, C. Wang and R. Q. Lu, "Modeling and monitoring of multimode process based on subspace separation," Chemical Engineering Research and Design, vol.91, no.5, pp.831–842, 2013.

[27] F. N. Zhou, C. L. Wen, T. H. Tang and Z. G. Chen, "DCA based multiple faults classification method," Acta Automatica Sinica, vol.35, no.7, pp. 971-982, 2009.

[28] P. Tamilselvan and P. F.Wang, "Failure classification using deep belief learning based health state classification," Reliability Engineering and System Safety, vol. 115, pp. 124–135, 2013.

[29] R. B. Huang, C. Liu, G. Q. Li, and J. L. Zhou, "Adaptive Deep Supervised Autoencoder Based Image Reconstruction for Face Recognition," Mathematical Problems in Engineering, vol. 2016, Article ID 6795352, 14 pages, 2016.

[30] H. M. Liu, L. F. Li, and J. Ma, "Rolling Bearing Fault Classification Based on STFT-Deep Learning and Sound Signals," Shock and Vibration, vol. 2016, Article ID 6127479, 12 pages, 2016.

[31] P. L. Wang , C. J. Xia, "Fault detection and self-learning identification based on PCA-PDBNs," Chinese Journal of Scientific Instrument, vol.36, no. 5, pp.1147-1154, 2015.

[32] R. Pang, Z. B. Yu,  W. Y. Xiong and H. Li , "Faults recognition of high -speed train bogie based on deep learning ," Journal of Railway Science and Engineering, vol.12, no.6, pp. 1283-1288, 2015.

[33] C. Lu，Z.Y. Wang, W. L. Qin and J. Ma, "Fault classification of rotary machinery components using a stacked denoising autoencoder-based health state identification," Signal Processing, vol.130, pp.377-388, 2017.

[34] F. Jia, Y. G. Lei, J. Lin, X. Zhou, and N. Lu, "Deep neural networks: A promising tool for fault characteristic mining and intelligent classification of rotating machinery with massive data," Mechanical Systems and Signal Processing, vol.72-73, pp. 303–315, 2016.

[35] Bearing data Centre, Case Western Reserve University, Available:

<http://csegroups.case.edu/bearingdatacenter/home>

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