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Research Article

Keywords: BP neural network, Deep confidence neural network, Coaxiality prediction, Multi-stage rotors

Posted Date: September 8th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1797873/v1

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A Prediction Model of Multi-stage Rotors Coaxiality
Based on Neural Network

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Abstract: For the assembly of multi-stage rotors, this paper proposes the coaxiality predicting model of multi-stage rotors based on neural network. The model takes the complicated operation of centering and tilting during the measurement of single-stage rotor machining error and the indeterminacy of saddle surface error transmission mechanism during the process of multi-stage rotors assembling into consideration. First of all, the paper proposes the depolarization and declination model of single-stage saddle surface rotor based on deep confidence neural network. And then, the single-stage rotor machining error is taken as the input amount into the BP neural network to establish the coaxiality predicting model of multi-stage saddle surface rotors. Finally, experimental measurements of the level-four core engine rotor are performed to verify the accuracy of multi-stage rotors coaxiality prediction model. The result shows that the coaxiality of multi-stage rotors can be effectively predicted by the neural network. The average error of coaxiality prediction is 1.0μm, the standard deviation is 0.7μm, compared to the traditional method, the mean error and standard deviation decreases by 81.8% and 73.1%, respectively, which can reflect the advantages of the coaxiality prediction model of BP neural network.

Keywords: BP neural network, Deep confidence neural network, Coaxiality prediction, Multi-stage rotors.

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1. Introduction

Multi-stage rotors are important parts of the engine, the performance and life of the engine are largely determined by the accuracy of rotor assembly[1,2]. Coaxiality is an important indicator to evaluate the performance of multi-stage rotors[3-5], off limits- error of coaxiality will intensify the vibration of rotor, reduce the performance of engine, also, it will make the rub between engine blade and cartridge receiver, and even further lead to the fracture of blade and some other serious hitches[6-7]. The method that can measure the coaxiality of multi-stage rotors accurately is urgently needed to meet the requirement of assembling multi-stage rotors precisely. Multi-stage rotors are made of single-stage rotor stacking stage by stage[8], because of machining error, the mating surface of rotor is complex, and the rotor error at all levels are transmitted step by step through the bidirectional rabbets of axial diameter[9]. Therefore, evaluation of single-stage rotor machining error is the basis of coaxiality prediction of multi-stage rotors. According to the appearance of axial measurement plane, the rotor can be divided into single-dip surface rotor and saddle surface rotor. Coaxial measurement of multi-stage rotors, which contain saddle surface rotor is more difficult. On the one hand, the machining error of saddle surface rotor includes concentricity and flatness, which is obtained by measuring data of rotor axial and radial measuring surfaces and datum plane profile jitter by assembly measuring instrument, and eliminating the rotor mounting eccentricity and tilt error through the error compensation algorithm. Due to the limitation of the error compensation algorithm, the rotor position is adjusted to make the mounting eccentricity and tilt error meet the requirements. The traditional method of centering and tilting adopts the manual adjustment method, and the process is complex and
ineffective. On the other hand, when the saddle surface rotor is assembled, rabbet mating surfaces between rotors contact by point, and the error transmission mechanism is not clear, so it is very difficult to predict the coaxiality of multi-stage rotors.

Nourmous scholars have conducted various studies for the evaluation of rotor machining error. Dan used the genetic algorithm to optimize the rotor concentricity prediction, and found that optimizing the installation phase of the rotor can improve the rotor assembly quality to some extent[10]. Zhao Z X et al. analyzed the effect of eccentricity and tilt error in solving the fitting diameter of the cylindrical profile on the basis of two-parameter measurement model and gave the results under four kinds of cylindrical profiles[11]. For the research of multi-stage rotors stacking assembly method, Sun et al. from Harbin Industrial University researched the problem that it is difficult to measure the coaxiality of multi-stage rotors on the basis of aeroengine multi-stage rotors assembly set model, they established the systematic location and orientation error transfer model of multi-stage rotors through the analysis of spatial vector projection characteristics of single-stage rotor location and orientation error during the process of multi-stage rotors assembling. The model enabled a significant improvement in measurement accuracy, with a 69% reduction in the coaxiality error of multi-stage rotors assembling by using this method compared to directly assembling[12]. Liu et al. of Dalian University of Technology, proposed the prediction method of centering error and relative deviation error of rotor assembly with the consideration of coaxiality factors, and established the prediction and stacking model with assembly accuracy in combination with the principle of homogeneous coordinate transformation[13].

In the process of research, due to special and complex appearance of the rotor and high quality in evaluation of rotor machining error, the problem of multi-stage rotors assembly is considered to be complex and difficult. On the other hand, deep learning theories has developed rapidly in recent years, and has shown strong non-linear mapping capabilities in the prediction of complex problems[14-17]. This paper investigates the possibility of using deep learning methods to predict the coaxiality of the multi-stage rotors assembling, which contains the saddle surface rotor. The structure of this paper is as follows, first of all, the deep confidence neural network is used to establish a machining error prediction model of single-stage rotor, which eliminates the complex process of manual centering and tilting during the traditional rotor machining error prediction. Then, the single stage rotor machining error, rotor assembly phase and tightening torque between rotors are used as inputs, and the multi-stage rotors assembly coaxiality is used as output to predict the multi-stage rotors assembly coaxiality by the BP neural network. Comparing the predicted values of model with the truth value obtained from the experimental measurements, the mean difference between the predicted concentricity error and true concentricity error of single-stage rotor is 0.1μm and the mean difference between the predicted flatness error and true flatness error of single-stage rotor is 0.7μm. The mean prediction error of coaxiality error of multi-stage rotors is 1.0μm and the standard deviation is 0.7μm. The predictive network has superior performance and can be used to guide the assembly of multi-stage rotors.

2. Mathematical Model

2.1 The Centering and Tilting Model of Saddle Surface Rotor Based on Deep Confidence Neural Network

Saddle surface rotor machining error includes concentricity and flatness, as shown in the “Figure 1”, with the axis, which is perpendicular to the center of the datum plane in axial direction as the reference, making the datum axis overlap with the high-precision turntable axis, the amplitude and eccentric angle of rotor concentricity error are obtained respectively by evaluating the measurement plane profile in radial direction after overlapping with the axis. Flatness error of saddle surface rotor, which is the distance between the farthest two planes that contain two sampling points of rotor axial measurement plane and are perpendicular to the datum axis can be gained by sampling the measurement plane profile of saddle surface rotor in axial direction after overlapping with the axis,
the highest sampling point angle of axial measurement plane is the angle of flatness error.

![Simplified diagram of saddle rotor.](image)

**Figure 1.** Simplified diagram of saddle rotor.

In order to obtain the machining error of the rotor, we need to perform the adjustment procedure of centering and tilting manually with the traditional evaluation method, which is not only tedious and time-consuming, but also reduces the accuracy of machining error evaluation. Deep learning method has the strong nonlinear fitting ability, with the influencing factors of rotor machining error as the inputs of the neural network, and rotor machining error itself as the output of the neural network, we can learn the complex predicting process of rotor machining error, solve the difficult problem of centering and tilting manually, and realize the prediction of rotor machining error. The method of deep confidence networks by greedy layer-wise pre-training of Restricted Boltzmann Machine (RBM)[18] not only improve the network training efficiency, but also optimize the problem that ordinary deep neural network can easily fall into the local optimality[19-21], so, the deep confidence neural network is used to establish the prediction model of saddle surface rotor machining error.

The deep confidence prediction network mainly contains two components, unsupervised pre-training and supervised trimming. Among them, the unsupervised pre-training is stacked by multiple RBMs and uses network inputs to train each RBM step by step, the structure of RBM includes visible layers and hidden layers, the kth hidden layer is not only the kth hidden layer of RBM, but also the (k+1)th visible layer of RBM, and the supervised trimming procedure depends on the BP neural network.

The network inputs of the concentricity deep confidence prediction network are perpendicularity of axial datum plane, eccentricity of radial datum plane and eccentricity of radial measurement plane, and the network output is concentricity error value or the angle of concentricity error value. As shown in the “Figure 2”, the prediction network of concentricity contains two hidden layers with the number of neurons of 13 and 4, respectively.

![Network structure of concentricity depth confidence prediction.](image)

**Figure 2.** The network structure of concentricity depth confidence prediction.
Because perpendicularity of axial datum plane, eccentricity of radial datum plane and eccentricity of radial measurement plane are all defined by the error value and the corresponding angle, the number of neurons in the input layer of the concentricity prediction network is 6, which contains error value and the corresponding angle. The number of neurons in the output layer is 1, which is the concentricity error value or its corresponding angle.

As shown in the “Figure 3”, the prediction network evaluates the concentricity of saddle surface rotor and its corresponding angle by the change in the cost function (MSE), and it turns out that when the number of iterations is below 2000, the decreasing trend of the cost function of neural network training and validation set is obvious and gradually flattening out, when the number of iterations reaches 2000, the cost function is basically zero, and the neural network training process is completed.

![MSE of concentricity error prediction network](image1)

(a) MSE of the concentricity error prediction network

![MSE of concentricity error angle prediction network](image2)

(b) MSE of the concentricity error angle prediction network

**Figure 3. MSE of concentricity error and its corresponding angle prediction network.**

The network inputs of the flatness deep confidence prediction network are flatness of axial measurement plane and flatness of axial datum plane, and the network output is flatness error value or the angle of flatness error value. As shown in the “Figure 4”, the prediction network of flatness contains three hidden layers with the number of neurons of 26, 10 and 6, respectively.
Sigmoid function is used as the activation function of hidden layer and identity function as the activation function of output layer.

The flatness of axial measurement plane and the flatness of axial datum plane include the error value and its corresponding angle, so the number of input layer neurons of the flatness prediction network is 4, and the number of neurons in the output layer is 1, that is, the flatness error value or its corresponding angle.

As shown in the “Figure 5”, when the number of iterations of the prediction network of the flatness of saddle surface rotor and its corresponding angle is below 1500, the decreasing trend of the cost function of neural network training and validation set is obvious and gradually flattening out with the increase of iterations, when the number of iterations reaches 1500, the cost function basically converges, and the neural network training process is completed, the cost function of validation set is about 0.02.
2.2. The Prediction Model of Coaxiality of Multistage Saddle Surface Rotor Based on BP Neural Network

When the saddle surface rotor is assembled, rabbet mating surfaces between rotors contact by point. Because the actual assembly process of tightening bolts of the multi-stage rotors depends on manual experience, tightening torques of bolts are hard to be consistent, and the uneven tightening force of bolts can lead to the irregular deformation of bolts connection surface[22,23], which has the great influence on assembly of multi-stage rotors because of the coordination mode of point contact of saddle surface rotor. Considering that neural networks can effectively fit the nonlinear mapping between input and output, this paper proposes a method to predict the coaxiality of the assembly of multistage saddle surface rotor with BP neural network.

As shown in the “Figure 6”, the multi-stage rotors are assembled in stacking way by single-stage rotors, and the rotors are connected by the structure of flange bolt group. The assembly method between the adjacent two rotors is the same, the radial and axial top front edge of the lower rotor cooperate with the radial and axial base front edge of the higher rotor respectively, making the lock tightly with the axial evenly distributed bolts on the rabbet contact surface. After assembly, the coaxiality of the multi-stage rotors is determined by the machining error of single-stage rotor,
installation phase of each rotor, and bolt tightening torque.

As shown in the “Figure 7”, the proposed model predicts the coaxiality of 4-stage rotor’s model, the network inputs of the BP neural network prediction model of rotor coaxiality are 22 characteristic values, which include the respective eccentric error values and eccentric angle of 4 rotor stages, respective perpendicularity error values and lowest point angle of 4 rotor stages, rotor assembly phase between adjacent stages and tightening torque between stages, so the number of input-layer neurons is 22. The network output is coaxiality of multi-stage rotors, and the number of neurons is 1.

![Figure 7. Concentricity BP neural network prediction model](image)

The proposed BP neural network prediction model contains a hidden layer, with sigmoid function as activation function and identity function as activation function of the output layer. The cost function $C_0$ is calculated with the minimum mean square error (LMS).

According to equation (1), improving the cost function by L2 regularization can improve the overfitting problem, which is easily generated during neural network training.

$$C = C_0 + \frac{\lambda}{2n} \sum w^2$$

In the equation, $C$ represents the cost function after L2 regularization, $w$ is the weight of the neural network, $\lambda$ is the regularization parameter, and $n$ represents the number of neurons in the input layer.

When $\lambda$ is too large, the cost function decays rapidly, and network training is insufficient. The improvement of neural network overfitting problem are not approving when it’s too small. When $\alpha$, which represents the learning rate, is too large, the neural network converges too fast, deviation of the prediction result is excessive and prediction network learning speed will be slow when it’s too small, making it a longer time to complete the training process. With the excessive number of neurons in hidden layer, the complexity of neural network increases, learning rate becomes slow, otherwise, it’s difficult to establish an effective mapping relationship between input and output of the neural network, or the prediction effect will become worse.

Thus, the prediction effect of coaxial BP neural network prediction model is mainly determined by three hyper-parameters: the regularization parameter $\lambda$, the learning rate $\alpha$ and the number of hidden layer neurons. The hyper-parameters are optimized by the particle swarm algorithm (PSO) [24-26].

The number of hidden layer neurons of rotor coaxial prediction network at level four is 48, with a learning rate of 0.038 and a L2 regularization coefficient of 0.005.

As shown in the “Figure 8”, when the number of iterations reaches 1200, MSE values of the validation set model are stable and converge to 0, and the training process of coaxiality prediction model is completed.
3. Experiment

3.1. Experimental device

To verify the validity of the single-stage rotor machining error prediction model of saddle surface rotor, which is based on deep confidence network and the coaxiality prediction model of multi-stage rotors based on BP neural network, an assembly meter, as shown in the “Figure 9” is used to measure the machining error of single-stage rotor and the coaxiality of multi-stage rotors. Parts 1~6 are air-bearing rotary table, centering and tilting table, three-jaw chuck, inductive sensor, horizontal guide rail and vertical guide rail. The precision parameters of the experimental device are shown in the “Table 1”.

![Figure 9. Photograph of experiment set-up: rotary measuring instrument](image)

**Table 1. Device accuracy of multistage rotor measuring device**

<table>
<thead>
<tr>
<th>Related parameters</th>
<th>Parameter accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial rotation accuracy of turntable(μm)</td>
<td>&lt;0.08</td>
</tr>
<tr>
<td>Axial rotation accuracy of the turntable(μm)</td>
<td>&lt;0.08</td>
</tr>
<tr>
<td>The minimum adjustment displacement of the self-aligning and tilting table(μm)</td>
<td>0.2</td>
</tr>
<tr>
<td>The minimum adjustment angle of the self-aligning and tilting table(´)</td>
<td>0.2</td>
</tr>
<tr>
<td>Inductive sensor resolution(μm)</td>
<td>0.1</td>
</tr>
</tbody>
</table>
3.2. Experimental Results of Machining Error Prediction

To investigate the effect of machining error prediction model of saddle surface rotor, which is based on deep confidence network, this paper evaluates the performance of the machining error prediction network with testing set samples.

As shown in the “Figure 10”, the trained concentricity prediction network is used on the prediction of testing sample data, the average difference between the predicted concentricity error value and the true concentricity error value is 0.1μm. The average difference between the angle of predicted concentricity error value and the angle of true concentricity error value is 0.9°. This paper uses the determination coefficient R2 to better evaluate the performance of prediction network and finds that R2 for the prediction network of concentricity error value and angle of the concentricity error value are both 0.99.

![Prediction result of concentricity error](image1)

![Prediction result of concentricity error angle](image2)

Figure 10. Prediction result of concentricity error and its corresponding angle.

As shown in the “Figure 11”, the average difference between the predicted flatness error value and the true flatness error value is 1.7μm. The value of R2 for the predicted network of flatness error is
0.94. The average difference between the angle of predicted flatness error value and the angle of true flatness error value is 18°. The value of R² for the predicted network of the angle of flatness error is 0.92. Compared to the prediction network of concentricity error, the effect of flatness error prediction network has decreased.

![Prediction result of flatness error](image1)

![Prediction result of flatness error angle](image2)

In conclusion, the prediction value of the machining error of saddle surface rotor basically meets the requirement of assembly process, which confirms the effectiveness of the machining error prediction method of saddle surface rotor based on deep confidence neural network.

### 3.3. Experimental Results of Coaxiality Prediction

The trained network is used to predict the 30 groups of test samples, and the prediction results are red dots shown in the “Figure 12”. Meanwhile, in order to verify the influence of assembly deformation of saddle surface rotor with the point contacting mode of mating surface has on the prediction of coaxiality of multi-stage rotors, 30 sets of test samples are predicted by the traditional coaxiality prediction method, and the prediction results are shown as blue triangles in the “Figure 12”. The actual
measurement results of the coaxiality error of 30 sets test samples are shown as yellow boxes in the “Figure 12”.

The coaxiality error of multi-stage rotors, which is obtained by using the BP coaxiality error prediction network is consistent with the actual measured coaxiality error trend. Furthermore, the average error of predicted coaxiality error with the BP coaxiality error prediction network is 1.0μm, standard deviation is 0.7μm and the maximum prediction error is 3.3μm. Compared to the traditional method, the mean error of the coaxiality error reduces by 4.5μm, and the standard deviation decreases by 1.9μm. It can be seen that the assembly deformation of saddle surface rotor has a great impact on the coaxiality error prediction of multi-stage rotors, the traditional coaxiality error prediction method has the low prediction accuracy without the consideration of deformation impact, and the BP coaxiality error prediction network has the superior prediction performance, which can be used to instruct the multi-stage rotors assembly procedure of aero-engines.

4. Conclusion

This paper establishes the machining error prediction model of saddle surface rotor based on deep confidence neural network and the coaxiality prediction model of saddle surface multi-stage rotors based on BP neural network with deep learning, following conclusions are drawn by the experimental verification:

Firstly, this paper proposes the deep confidence neural network prediction model to solve the problem that the process of centering and tilting during traditional machining error measurement of aero-engine rotor is complicated and time-consuming. Then, it proposes the method with BP neural network to predict the coaxiality of saddle surface multi-stage rotors in order to find the optimal assembly phase and guide the assembly of multi-stage rotors. The result shows that the average prediction error of concentricity prediction network and flatness prediction network are 0.1μm and 1.7μm, the R2 determination coefficient is 0.99 and 0.94, respectively, and the prediction accuracy of machining prediction network meets the requirement of field assembly. Moreover, the coaxiality prediction error of multi-stage rotors based on BP neural network has an average error of 1.0μm and a standard deviation of 0.7μm, which compared to the traditional method, the mean error and standard deviation decreases by 81.8% and 73.1%, respectively, showing the advantages of this prediction method.

Due to the difficulty of centering and tilting manually during the measurement of machining error of saddle surface rotor and the indeterminacy of error transmission mechanism of multi-stage rotors
during assembling, this paper proposes the prediction model based on deep confidence neural network and the prediction model based on BP neural network, which improved the accuracy of the coaxiality prediction of saddle surface multi-stage rotors and optimized the efficiency of rotor assembly. In future studies, parameters of the BP neural network can be optimized and other neural network models can be implemented to predict the coaxiality of multi-stage rotors.

Author contribution

All the related authors contribute to the conceptualization; data curation; investigation; methodology; writing—original draft; writing—review; and editing of the manuscript.

Acknowledgements

We are grateful to the following funds for their assistance: National Key R&D Program of China (grant number 2021YFF0603200), Natural Science Foundation of Heilongjiang Province of China (grant number JJ2020LH0172), China Postdoctoral Science Foundation (grant number 2021T140164), Heilongjiang Postdoctoral Fund (grant number LBH-TZ2112), National Natural Science Foundation of China (grant number 52175498

Funding

This work was supported by National Key R&D Program of China (grant number 2021YFF0603200), Natural Science Foundation of Heilongjiang Province of China (grant number JJ2020LH0172), China Postdoctoral Science Foundation (grant number 2021T140164), Heilongjiang Postdoctoral Fund (grant number LBH-TZ2112), National Natural Science Foundation of China (grant number 52175498)

Availability of data and materials

Data used in this work have been properly cited within the article.

Ethics approval

The article has been written by the stated authors who are all aware of its content and approve its submission.

Consent for publication

All listed authors approve to publish.

Conflict of interest

The authors declare no competing interests.

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