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Abstract: Motorized spindle is one of the key components of CNC machine tools,it aims to predict the future reliable working time of the equipment, provide support for maintenance decisions. It is of great significance to reduce maintenance support costs and improve the stability of the equipment .This paper proposed a model to estimate the reliable running time based on health indicator, which is used as an index to monitor the health status of the motorized spindle, and the health index model is established based on single feature parameter, and then the multiple characteristic parameters respectively,with proper modification .The health indicator is used to fit the exponential model based on time series analysis to predict the health trend of the motorized spindle over time, and to estimate the reliable running time in the future. An example was presented to verify the rationality and feasibility of the proposed model. The results showed that the health indicator model is effective and could predict the reliable running time of motorized spindle.

Key words: Health indicator;Motorized spindle;Reliable running time

1. Introduction

Reliable running time estimation, as an important core technology for fault prediction and health management, is also the most difficult and most challenging comprehensive technology. It aims to predict the future reliable working time of the equipment, provide support for maintenance decisions. It is of great significance to reduce maintenance support costs and improve the stability of the equipment .However, as one of the core components of the machine tool, the motorized spindle has the characteristics of high accuracy, long life and high reliability, and it is difficult to obtain the motorized spindle failure life data through reliability experiments in a short time[1-2].The traditional reliability method needs to obtain the failure life data of the product to infer the overall reliability [3]. When the product life is longer and the reliability higher, it is difficult to obtain its failure life data in a short time. Therefore,for the motorized spindle with high reliability and long life, this paper adopts the degradation data based on state detection, through the change of some characteristic parameters in the degraded data to achieve the purpose of detecting the safe operation of motorized spindle equipment, excavates and abstracts the characteristic information hidden in a large number of condition monitoring data and failure models to reflect the healthy state of the equipment. Rely on real data and reliable methods to evaluate the health status of the equipment itself, establish the health file for the whole life cycle of the equipment, and provide the basis for the decision of equipment maintenance and support.So as to carry out ideal maintenance on the basis of the state monitoring.The health index [4-5] is a quantitative value used to measure and characterize the health status of the equipment. The current status of the equipment can be used to judge the current status of the equipment.Then, combined with the historical test data and real-time performance information, the changing trend of the health index with time is fitted, and the distribution of the health index with time at a certain time in the future can be predicted. Estimate the reliable running time of the motorized spindle.

At present, many experts and scholars have done a lot of research on the reliability and remaining useful life of the motorized spindle, but it is almost blank to estimate the reliable running time by combining multiple characteristic parameters in the field of motorized spindle. Previous reliability evaluations of motorized spindle included both fault-free data and those based on the performance degradation data of motorized spindle and failure data. But most of them are based on a certain key parameter as the research point to evaluate the reliability and remaining useful life of the motorized spindle. Lack of comprehensive comprehensive health assessment.With no fault data:Jiang Xi [6] and others based on the Bayes method combined with the virtual augmented sample method to study the reliability of the motorized spindle. Finally, the reliability evaluation results of the motorized spindle were obtained and the rationality was verified.References [7-9] also made an in-depth study of the Bayes method and its application .In terms of performance degradation data of motorized spindle: Qiu Ronghua [10] et al. established a degradation model of the motorized spindle based on the degradation data of the radial jump of the motorized spindle,and obtained its service life .Chi Yulun [11] et al. used the acoustic emission signal as the performance measurement of the machine tool spindle, established a degradation model, obtained the failure life, and combined the virtual augmented sample method to evaluate the machine tool spindle reliability.When there is failure data of the motorized spindle failure: Zhao Jinping [12] and other statistics and analysis of the failure data, forming observation samples, and fitting the probability density distribution function and cumulative distribution function curve of the equipment failure interval time, so as to infer The distribution law obeys the Weibull distribution. Finally, the reliability evaluation indexes of the equipment were calculated based on the statistical results.Yang Bin [13] established a reliability covariant regression model considering multiple performance degradation to realize the reliability evaluation of the motorized spindle. The proposed method overcomes the problem that it is difficult to carry out analysis without failure data in the traditional reliability assessment work and provides a reference for the reliability assessment work under accelerated test.Foreign scholars Jayaram [14] and others put forward an analysis model of product performance degradation data, and analyzed and predicted the real-time reliability level of the spindle products using the maximum likelihood method.

But the research on health index mostly focuses on the remaining battery life and circuit equipment. The remaining battery life research:Lu Zhaoquan [15], etc. proposed the estimation of lithium battery power based on health factors. The experimental data and Matlab simulation proved that the method has high feasibility.Pang Jingyue [16] and others proposed a method framework for constructing a health factor for predicting the remaining life of lithium-ion batteries by using charge-discharge detection parameters of lithium-ion batteries, and a method system for predicting the remaining life of lithium-ion batteries online.In terms of circuit equipment:Zhang Fengxia [17] and others proposed the life prediction method of track circuit equipment based on health index. The feasibility is verified through an example and it provides a theoretical basis for the maintenance of the equipment by the relevant maintenance department.Shi Changkai [18] and others made quantitative assessment of distribution network risk based on the real-time health index of equipment. The examples show that the proposed method can obtain the failure rate, failure time and load risk of various load points, and prove the effectiveness of a quantitative assessment method for distribution network risks based on real-time health index.Chunbo Yang [19] and others proposed the evaluation of equipment health status based on the comprehensive health index. An example is used to analyze the effectiveness and rationality of the method.

This paper establishes a complete model for evaluating the health status of motorized spindle. It considers both single feature degradation and multiple feature degradation, and comprehensively considers the balance between feature parameters to obtain a comprehensive health index formula. Finally, the change trend of the comprehensive health index over time based on the time series is established,so that the purpose of predicting the reliable running time of the motorized spindle in the future is achieved,the equipment can be repaired in time and the safety of the equipment is improved .

2. Reliable running time prediction

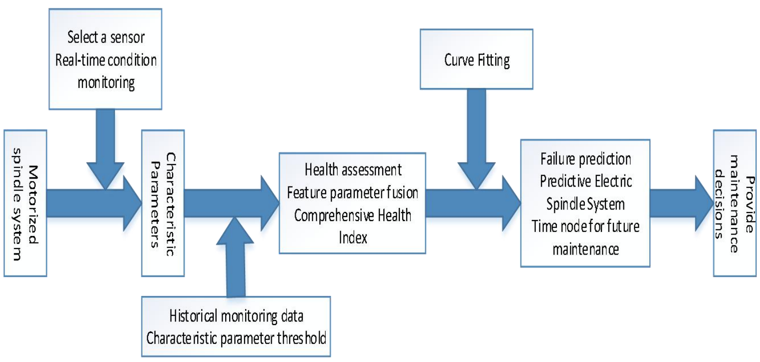

Figure 1. Predictive framework of reliable running time of motorized spindle based on comprehensive health index

As shown in Fig. 1, firstly,appropriate sensors are selected for the motorized spindle system to monitor the real-time status of the motorized spindle. The obtained historical status monitoring data are extracted for characteristic parameters, and representative and convenient characteristic parameters are selected.According to the formula of comprehensive health index, the obtained characteristic parameters were weighted for the first time according to the order relation method.Order relation analysis is an analytical method combining qualitative analysis with quantitative analysis.However, because the order relation method has strong subjectivity, in order to exclude the influence of subjective factors, the entropy weight method is used for the second weighting to achieve the unification of main and objective.Then the comprehensive health index is obtained according to the formula of comprehensive health index.After that, the curve fitting of the historical comprehensive health index was carried out to obtain the curve of the comprehensive health index over time, and the fault prediction was carried out to predict the future reliable running time of the motorized spindle, so as to carry out maintenance in advance and provide maintenance decisions.

3. Health indicator of motorized spindle

3.1 Health index with single feature parameter

the Health Index of motorized spindle is usually denoted as HI, and the value range of HI is defined as [0, 1]. The closer the HI is to 1, the better the Health state of the equipment is; the closer it is to 0, the worse the Health state is.1 means best condition, 0 means complete failure.

During the operation of motorized spindle, the standard value of each index changes continuously with time.Through the design parameters of the equipment and certain historical statistical data, the state degradation quantities $x_{i,j}$ (t) of this parameter and the minimum limit value x_{min} and maximum limit value x_{max} of this indicator parameter can be obtained.When the actual measured value exceeds the threshold range, the health index is 0, and the machine should be stopped immediately for maintenance.When the actual measured value coincides with the standard value, the health index is 1, which is the best condition of the equipment.When the actual measured value is between the threshold range, the value between [0,1] can be obtained to quantify the equipment state. The normalization is calculated as follows:

$$h_{i,j}(t) = \frac{x_{max} - x_{i,j}(t)}{x_{max} - x_{min}} \quad (1)$$

Where $h_{i,j}(t)$ is the health index based on the characteristic parameter x_j of device i; $x_{i,j}(t)$ is the measured value of characteristic parameter x_j at time t; x_{max} is the maximum value and x_{min} is the minimum value.

3.2 Health index with multiple feature parameters

During the operation of the spindle, there will be a lot of degraded data, such as vibration, current, voltage, temperature, noise, etc.Due to the complexity of the equipment operating environment, it is often difficult to evaluate the whole equipment operating state by the change of the characteristic parameters of the single state of the equipment.In this paper, the comprehensive weighting method is adopted to evaluate the health state of multiple feature parameters of the equipment. The weight value reflects the importance of each feature parameter on the operation state of the equipment, and reasonable weight distribution is the basis for accurate evaluation of the operation state of the equipment.Order relation analysis is an analytical method combining qualitative analysis with quantitative analysis. First, the mutual importance of feature parameters is compared in pairs, and the importance of feature parameters is sorted according to the expert experience:$y_1 > y_2 > y_3 > y_4$............Then determine the relative importance between the two adjacent indicators yj+1 and yj, and obtain the weight coefficients of each characteristic parameter as follows:

$$p_{j+1} = \left(1 + \sum_{j=1}^{n-1} \prod_{k=j}^{n-1} \frac{y_j}{y_{j+1}}\right)^{-1} \quad (2)$$

$$p_j = \left(\frac{y_j}{y_{j+1}}\right)^{-1} p_{j+1},\ \ j=1,2,\ldots n-1 \quad (3)$$

In the formula, pj is the weight value of the j-th characteristic parameter obtained by the order relationship method.

Due to the influence of subjective arbitrariness on weight allocation in order relation method, the results depend on expert experience knowledge. In order to eliminate the influence of subjective factors, an entropy weight method based on objective data relationship is used to redistribute weight.Entropy weight method is a method to obtain the entropy weight of each characteristic parameter through information entropy based on the variation degree of the characteristic parameter, and then obtain the weight of each characteristic parameter.The greater the difference of an index, the smaller the entropy weight, indicating that the index provides more information, plays a greater role in the evaluation, and the greater the weight.The calculation formula is:

$$y'_{i,j} = \frac{y_{i,j}}{\sum_{i=1}^{m} y_{i,j}} \quad (4)$$

$$e_j = -\frac{1}{\ln n} \sum_{i=1}^{m} y'_{i,j} * \ln y'_{i,j} \quad (5)$$

$$q_j = \frac{1-e_j}{n-\sum_{j=1}^{n} e_j} \quad (6)$$

Where: yi,j is the sample data; $y'_{i,j}$ is the proportion of the i-th sample data under the j-th feature parameter;m is the number of sample data; n is the number of feature parameters;ej is the entropy weight of the j-th feature parameter; qj is the weight value of the j-th feature parameter obtained by the entropy weight method. In order to make the combination weights as close to p and q as possible to achieve subjective and objective unity, an optimization model of the least square method is established to obtain the combination weights.

$$\min H(\omega) = \begin{Bmatrix} \sum_{j=1}^{n} [(\omega_j - p_j)^2 + (\omega_j - q_j)^2] \\ s.t. \sum_{j=1}^{n} \omega_j = 1, \omega_j \geq 0, j = 1,2,3\ldots..n \end{Bmatrix} \quad (7)$$

The expression of equipment health index based on multiple characteristic parameters is as follows:

$$h_i(t) = \sum_{j=1}^{m} \omega_j h_{i,j}(t) \quad (8)$$

Among them, $h_i(t)$ is the health index of the device; m is the number of characteristic parameters; ω_j is the combined weight of the j-th characteristic parameter, which reflects the influence of this parameter on the state of the device. $0 \leq \omega_j \leq 1$ ，且$\sum_{j=1}^{m} \omega_j = 1$

3.3 Health indicator model

The relationship between the health of power equipment and time can be characterized as:

$$H = H_0 \times e^{B*(t-t_0)} \quad (9)$$

This formula is derived from an empirical formula of the British EA company [20], where H represents the health status of the power equipment, which is continuously increasing with the use of time. The larger the value, the worse the health status, and the lower the value, the better the health status. The health index required by this article is continuously decreasing with the continuous use time. Therefore, in order to be applicable to the remaining reliable running time evaluation model of the motorized spindle of this article, it is improved and the improvement is as follows:

$$H_i(t) = 1-(1-H_0)*e^{B(t-t_0)} \quad (10)$$

In the formula: H0 is the health index at the time t0 of the device, taking 0.95, quoted from the literature [20].

$h_i(t)$ is the health index of the device at time t;

B is the aging coefficient;

t0 is the time when the equipment is initially put into operation;

t is the time when the equipment is evaluated;

In order to obtain its value, the expected operating life Td and aging coefficient B of the motorized spindle must be obtained first. The two calculation formulas are:

$$T_d = \frac{T_D}{f_1 * f_2} \quad (11)$$

$$B = \frac{\ln(1-HI_{ty}) - \ln(1-H_0)}{T_d} \quad (12)$$

Where: TD is the design life of the equipment;

f1 is the load correction coefficient, which is about 1.05; f2 is the environmental correction coefficient, which is about 1.05, which is quoted from the literature [19];

HI_{ty} is the health index when the equipment is decommissioned, which is generally taken as 0.2, which is quoted from the literature [20].

Taking the aging of equipment into consideration, defining a variable health factor is defined as:

$$\mu = \frac{\mathrm{Hi(t)}}{\mathrm{H_0}} \quad (13)$$

As the motorized spindle runs for a long time, its degradation generally follows an exponential form. Therefore, the comprehensive health index of the motorized spindle after the weighted and variable health factor correction is:

$$\mathrm{HI(t)} = \mu \cdot \mathrm{hi(t)} \quad (14)$$

HI(t) is a quantified expression of the comprehensive operating state. With the continuous operation of the motorized spindle, its changing trend also presents complex changing characteristics. In order to be able to correctly predict the future health status of the motorized spindle and the time nodes that need to be maintained, a health index sequence that can reflect the time-varying health status of the motorized spindle HI (t) = {HI (t1), HI (t2), ..., HI (tn)}. And build a suitable prediction model to describe this sequence. By collecting the historical monitoring data of the motorized spindle, a comprehensive health index is obtained, and these data are fitted using the Matlab curve fitting toolbox to obtain a function image in the form of an index of health index and time to establish a life cycle health curve. The exponential model constructed is as follows:

$$\mathrm{HI}(t) = a * e^{k \cdot t} \quad (15)$$

4. Case for verification

In this experiment, experimental data from reference [21] were selected and there was only one characteristic parameter, so its weight was 1.Some test data are shown in table 1:

Table 1 The corresponding radial jump at different times

	Time (h)									
	12	24	36	48	60	72	84	96	108	120
Sample 1	6.4	6.8	6.9	7.0	6.4	6.2	6.8	7.1	7.1	7.0
Sample 2	5.6	5.6	6.3	6.4	5.9	6.5	6.6	6.7	6.1	6.1
	Time (h)									
	132	144	156	168	180	192	204	216	228	240
Sample 1	7.3	7.4	7.9	7.6	7.1	7.4	7.3	7.6	7.2	7.5
Sample 2	5.8	5.8	5.9	6.2	6.7	6.2	6.7	6.7	6.3	6.1
	Time (h)									
	252	264	276	288	300	312	324	336	348	360
Sample 1	8.2	8.3	8.2	8.4	8.7	8.5	8.8	8.4	8.5	8.5
Sample 2	6.8	7.2	6.8	6.7	6.6	7.1	6.7	6.5	6.9	7.3

The motorized spindle has been running for 360h, and its normal value should be between 5.0-20um.The expected operating life of TD is 2500h and 12000h respectively.The expected operating life Td is 2268h and 10884h, respectively. The calculated comprehensive health index is shown in Table 2:

Table 2 Corresponding health index at different times

	Time (h)									
	12	24	36	48	60	72	84	96	108	120
Sample 1	0.94	0.93	0.93	0.92	0.92	0.91	0.91	0.90	0.90	0.90
Sample 2	0.97	0.97	0.96	0.97	0.96	0.96	0.96	0.96	0.96	0.96
	Time (h)									
	132	144	156	168	180	192	204	216	228	240
Sample 1	0.89	0.89	0.88	0.88	0.87	0.87	0.87	0.86	0.86	0.85
Sample 2	0.96	0.96	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
	Time (h)									
	252	264	276	288	300	312	324	336	348	360
Sample 1	0.85	0.85	0.84	0.84	0.83	0.83	0.83	0.82	0.82	0.81
Sample 2	0.95	0.95	0.94	0.94	0.95	0.94	0.94	0.94	0.94	0.94

According to expert experience, the health status is divided into the following five levels [19], and the mapping relationship is shown in Table 3:

Table 3 Health Index Rating

grade	Health index value range	Health level	Health description
First level	[0.8-1]	health	Very good health and safe equipment
Secondary	[0.6-0.8]	Healthier	Good health and safe equipment
Third grade	[0.4-0.6]	Sub-health	The equipment is not safe, and there is a slight abnormality. Monitoring and troubleshooting should be strengthened
Fourth grade	[0.2-0.4]	malfunction	The equipment is very unsafe and serious abnormalities should occur, and maintenance should be arranged as soon as possible
Fifth grade	[0-0.2]	Serious failure	Device does not work

These two axes have been running for 360 hours, with health indices of 0.81 and 0.94. Still in good health. Now, the first 20 groups of health indexes calculated will be fitted using MATLAB toolbox, and the obtained fitting curves are shown in Figures 1 and 2 respectively:

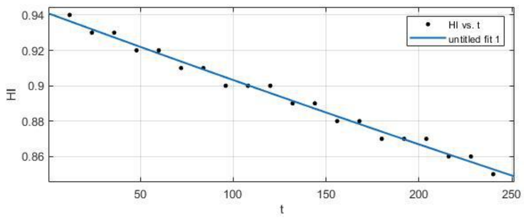

Figure 1 Curve fit of the first 20 sets of data for sample 1

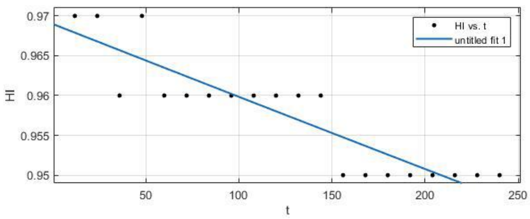

Figure 2 Curve fit of the first 20 sets of data for sample 2

The obtained expressions about the comprehensive health index of the motorized spindle are:

$$HI_1(t) = 0.9411 \cdot \exp(-4.109 \times 10^{-4} \cdot t) \quad (16)$$

$$HI_2(t) = 0.969 \cdot \exp(-9.495 \times 10^{-5} \cdot t) \quad (17)$$

According to the expressions of the two comprehensive health index, the health index of group 30 are predicted to be 0.81 and 0.94, respectively. As before, it is proved that the expression of the comprehensive health index function obtained by the fitting is reliable.

According to the comprehensive health index expression, the change curves of the health index over time are shown in Figure 3 and Figure 4, respectively:

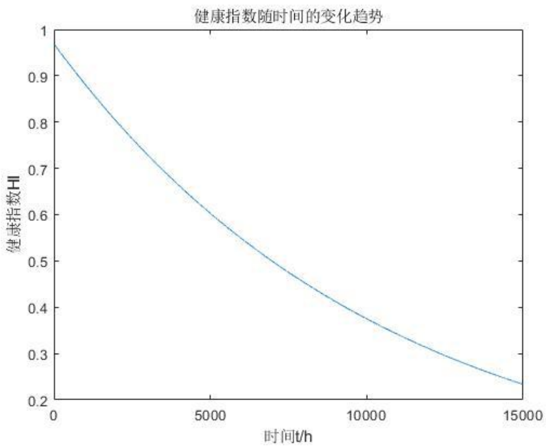

Figure 3 Health curve of sample 1

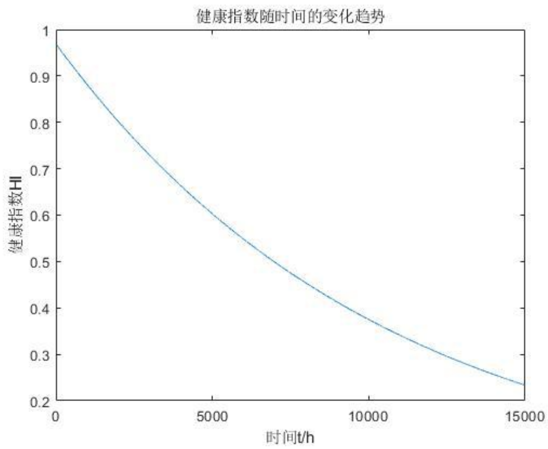

Figure 4 Health curve of sample 2

The graph obtained by putting two curves on one graph is shown in Figure 5:

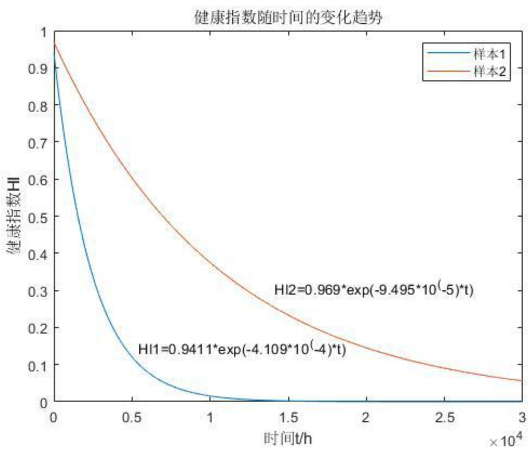

Figure 5 Health curve of samples 1 and 2

According to Table 3, when the health level reaches the third level, that is, when HI = 0.6, t is equal to 1120 and 5048, so when the motorized spindle runs for 760h and 4688h respectively, it will enter the third level. Monitoring and troubleshooting should be strengthened. When the health level reaches level four, that is, when HI = 0.4, the equipment is very unsafe and serious abnormalities occur, and maintenance should be arranged as soon as possible to obtain t equal to 2082 and 9318, respectively.There is little difference between the experimental results of 2500 and 12000 in reference [21]It proves that the proposed method is feasible. The future reliable running hours of the two motorized spindles are 1722h and 8958h, respectively.

5. Conclusion

This paper adopts the method of reliable running time estimation of motorized spindle based on comprehensive health index.By using the health index as a measure of spindle health,the health index formulas were obtained for single and multiple characteristic parameters.In addition, the weighted method combining order relation analysis and entropy weight method is adopted for data fusion of multiple feature parameters to achieve the unity of subjective and objective.Then the formula of comprehensive health index is obtained by modifying the health factor.Finally, an exponential model based on time series analysis is established to fit the change trend of the comprehensive health index of motorized spindle with time, so as to solve the problem of reliable working time estimation of motorized spindle in the future.An example is given to verify the rationality and feasibility of the proposed method.The obtained curve graph in the form of exponential function also conforms to the performance degradation law of motorized spindle.Finally, it is concluded that the two motorized spindles will enter the third sub-health state after 760h and 4688h respectively. Therefore, it is necessary to strengthen the monitoring and troubleshooting.The results show that the proposed method is effective and reasonable.It can achieve the purpose of reliable working time estimation of motorized spindle.Compared with the Bayes method in reference [21], it is found that there is some error, but the error is not large.Within the scope of permission.Finally, the future reliable running time of motorized spindle is obtained.In addition, this paper applies the concept of health indicator to the motorized spindle system for the first time, which has never been done before. Moreover, it can combine various monitoring data to make the reliable running time of motorized spindle more comprehensive, which is more advantageous than literature [21].However, there are still some shortcomings. Since there are only experimental data of degradation quantity, this paper only uses a single characteristic quantity to measure the degradation characteristic of motorized spindle. If there are more other degradation data, it will be better to conduct curving verification.I hope I can continue to improve in the future.

6. Thanks

On the completion of this paper, first of all, I would like to thank my mentor, Liting Fan. Ms. Fan guided me very patiently from the selection of the thesis direction from the beginning to the completion of the final essay. She provides me with a lot of literature and suggestions, tells me the details that should be paid attention to, and points out the errors carefully. Her research on the motorized spindle system and her profound insights on the subject have benefited me a lot. Teacher Fan's untiring work style, meticulous work attitude, and serious academic style have left me with a profound impact, and it is worthy of me to study forever. Here, I would like to extend my high respect and heartfelt thanks to the Teacher Fan!

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