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Research on the Consistency Evaluation of the Spindle Unit Stiffness Based on Comprehensive Weights

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Abstract: The spindle unit is the core component of a machine, and its stiffness is a key performance characteristic. The stiffness consistency is a key index to measure the stiffness of spindle units; however, there is a lack of unified evaluation methods for the spindle unit stiffness consistency. This paper proposes a comprehensive method for the evaluation of the spindle unit stiffness consistency based on fluctuations and comprehensive weights. First, the consistency of the spindle unit stiffness evaluation indices is expressed based on the fluctuations. Secondly, the subjective and objective weights of the spindle unit stiffness evaluation indices are given based on the AHP and CRITIC weight assignment methods. To obtain the comprehensive weights of the evaluation indices, the subjective and objective weights are synthesized based on the linear weighting method. Then, the consistency level of the spindle unit stiffness is obtained by the weighted summation of the comprehensive weights and fluctuations of the evaluation indices. Finally, the stiffness consistency of a group of spindle units is evaluated based on this method, and the evaluation result shows a 10.63% fluctuation, which indicates that its stiffness consistency level is class B, in line with the factory production requirements.

Keywords: spindle unit stiffness; consistency; fluctuation; comprehensive evaluation

Citation: Sun, F.; Jiang, Y.; Zhou, R.; Zhang, Q.; Xu, F.; Zhao, C.; Zhao, H.; Yang, W.; Li, B.; Bai, S. Research on the Consistency Evaluation of the Spindle Unit Stiffness Based on Comprehensive Weights. *Machines* **2024**, *12*, 426. https://doi.org/10.3390/machines12060426

Academic Editor: Kai Cheng

Received: 19 May 2024
Revised: 12 June 2024
Accepted: 19 June 2024
Published: 20 June 2024

1. Introduction

The spindle unit is one of the core functional components of a machine tool, and the quality of its performance depends, to a certain extent, on the degree of development of the machine tool. The spindle unit stiffness directly affects the machining accuracy of the machine tool [1]. Spindle units are important in the manufacturing industry and in terms of economic development. However, for many years, the spindle unit has been unstable, with low reliability, poor retention, and other problems, especially regarding the key criterion for the determination of the quality of the spindle unit stiffness. These problems lead to the quality of the spindle unit not being effectively guaranteed. The spindle unit stiffness consistency is a key indicator that can effectively reflect the stability, reliability, and maintainability of its stiffness. Therefore, it is of great significance to carry out research on spindle unit stiffness consistency evaluation methods and realize the effective evaluation of its consistency to guarantee the reliability and stability of the spindle unit.

In research related to the consistency evaluation of machines, several scholars [2–4] have defined the concept of consistency as the degree of approximation of the evaluated object in terms of statistical significance to the ideal value, based on the evaluation and analysis of the consistency and accuracy of machined parts. Some scholars [3–10] have analyzed the consistency of the straightness of the machine guideway and optimized the matching scheme of the guideway assembly process based on the difference in the consistency results, which provides a new idea for the evaluation of consistency. In the evaluation of objects containing multi-indices, the most commonly used evaluation method is the weight assignment method [11]. Weight assignment methods are categorized into subjective and objective weight assignment methods. The most widely used subjective weight assignment method among researchers is the AHP, which has the advantages of logical clarity and simplicity in calculation [12,13]. Objective weight assignment methods include the standard deviation method, the entropy weight method, the CRITIC weight assignment method, and so on. Among them, the CRITIC weight assignment method considers not only the effect of the coefficient of variation on the indices, but also the correlation between the indices at the same time. It determines the weights through the comparison of the intensity of the contrast and the degree of conflict between the evaluation indicators [14]. In addition to this, the correlation consistency or weights, such as affiliation, significance, and process capability indices, can be used to assist in the analysis of the evaluation results [15,16].

At present, the consistency evaluation method mainly focuses on the evaluation of the consistency levels of single-index evaluation objects. There is no unified methodology for the evaluation of the consistency of an object that contains multi-indices. Therefore, it is necessary to carry out research on the consistency evaluation of the spindle unit stiffness, which includes several evaluation indices. This paper establishes a consistency evaluation method based on the spindle unit stiffness, which compensates for the gap in this area.

2. Evaluation Index System for Spindle Unit Stiffness

Taking the consistency of the spindle unit stiffness as the evaluation object, there are a number of evaluation indices. The spindle unit stiffness evaluation indices include the dynamic stiffness, intrinsic frequency, axial static stiffness, and radial static stiffness, as shown in Figure 1.

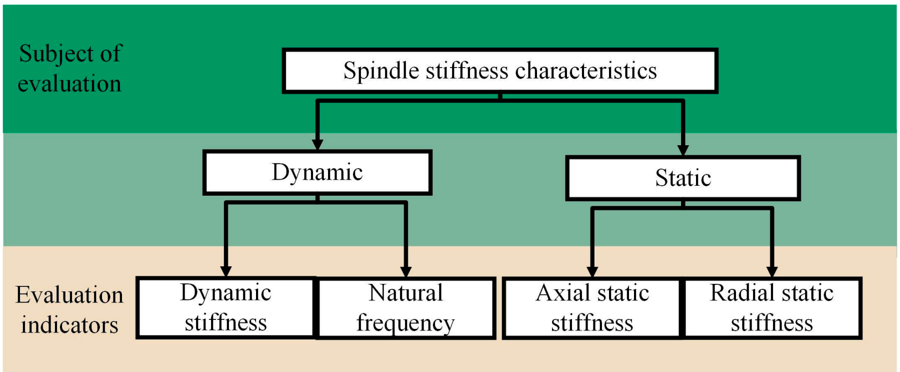

Figure 1. Evaluation indices for spindle unit stiffness.

The expression for the dynamic stiffness in the spindle unit stiffness evaluation index is

$$K_d = \frac{F}{A} = K\sqrt{\left(1 - \frac{\omega^2}{\omega_n^2}\right)^2 + \left(2\xi\frac{\omega}{\omega_n}\right)^2} \tag{1}$$

where F is the amplitude of the excitation force, A is the amplitude, K is the static stiffness, m is the system mass, $\omega_n = \sqrt{\frac{K}{m}}$ is the intrinsic angular frequency, $\xi = \frac{r}{r_c}$ is the damping ratio, r is the damping coefficient, and $r_c = 2m\omega_n$ is the critical damping coefficient.

The dynamic stiffness expression can be simplified as

$$K_d = \frac{F}{A} = K\sqrt{(1-\lambda^2)^2 + (2\xi\lambda)^2} \tag{2}$$

where λ is the angular frequency ratio and $\lambda = \frac{\omega}{\omega_n}$.

From Equation (2), a direct relationship exists between the dynamic stiffness, damping ratio, and angular frequency ratio. To obtain the variation in the dynamic stiffness K_d with the change in the angular frequency ratio λ, the partial derivatives are obtained for K_d with respect to λ. The partial derivative relation can be obtained. The damping ratio ξ of 45 steel, a commonly used material for spindles, is much smaller than 1, so it can be assumed that ξ^2 is a second-order small quantity. Ignoring the higher-order parameters due to the partial derivatives of the relationship, the equation can be simplified to

$$\frac{\partial K_d}{\partial \lambda} = \frac{K}{2} \frac{1}{\sqrt{(1-\lambda^2)^2 + (2\xi\lambda)^2}} [4\lambda(\lambda+1)(\lambda-1)] \quad (3)$$

From Equation (3), it can be seen that when the angular frequency ratio $\lambda \in (0,1)$, the partial derivative $\frac{\partial K_d}{\partial \lambda}$ is less than 0, and K_d is inversely proportional to λ. Because λ and ω_n are inversely proportional to each other, it can be deduced that the spindle's intrinsic frequency is positively correlated with the dynamic stiffness.

Based on the above analysis, it is known that the spindle's dynamic stiffness is determined by the spindle's static stiffness and intrinsic frequency, and the dynamic stiffness can be replaced by the spindle static stiffness and intrinsic frequency as two evaluation indices. In order to simplify the evaluation, the evaluation indices of the spindle unit stiffness are adjusted to include the intrinsic frequency, axial static stiffness, and radial static stiffness.

3. Consistent Evaluation Method for Spindle Unit Stiffness

The consistency in the stiffness of the spindle unit is expressed by the consistency and comprehensive weights of its evaluation indices, weighted and summed. In this paper, consistency is expressed as a fluctuation, which expresses the degree of dispersion of a set of data from its mathematical expectation or design ideal in a statistical sense.

The flowchart for the evaluation of the spindle unit stiffness consistency is shown in Figure 2.

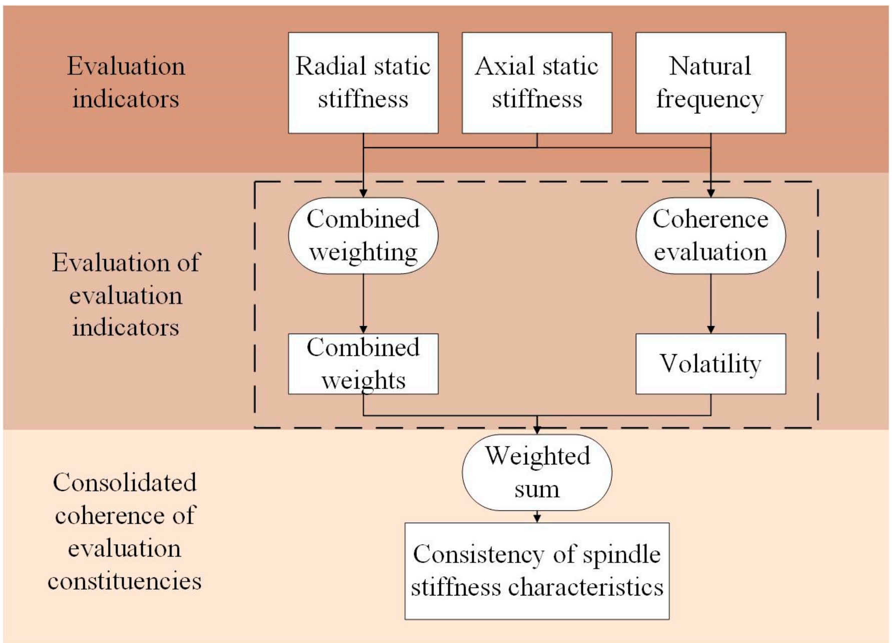

Figure 2. Evaluation methodology flowchart.

The stiffness consistency of the spindle unit is obtained by the weighted summation of the fluctuations and comprehensive weights of its evaluation indices (radial static stiffness, axial static stiffness, and intrinsic frequency). The expression for the spindle unit stiffness consistency B_z is

$$B_z = WB = \begin{bmatrix} w_r & w_a & w_g \end{bmatrix} \begin{bmatrix} B_r & B_a & B_g \end{bmatrix}^T \tag{4}$$

where w_r, w_a, and w_g, respectively, represent the comprehensive weights of the radial static stiffness, axial static stiffness, and intrinsic frequency of the spindle unit stiffness evaluation indices. B_r, B_a, and B_g, respectively, represent the spindle unit stiffness evaluation indices of the radial static stiffness, axial static stiffness, and inherent frequency fluctuation.

The comprehensive weight of the axial static stiffness of the spindle unit stiffness evaluation indices is obtained by linearly weighting its subjective and objective weights, and its expression is

$$w_a = \eta_o w_{oa} + \eta_s w_{sa} \tag{5}$$

where w_{oa} is the subjective weight of the evaluation index axial static stiffness, w_{sa} is the objective weight of the evaluation index axial static stiffness, and η_o and η_s are the weighting coefficients of the subjective and objective weights of the evaluation index, respectively. By analogy, the comprehensive weights of the radial static stiffness and intrinsic frequency of the spindle unit stiffness evaluation indices can be obtained as w_r and w_g.

3.1. Methodology for the Consistency Evaluation of Individual Evaluation Indices

An evaluation index's volatility indicates the relative degree of change between multiple measurements, i.e., the degree of deviation in the characteristic values of the mass-produced spindle unit stiffness evaluation index from its target value or mathematical expectation. The fluctuation evaluation process for the spindle unit stiffness evaluation index is as follows:

$$\bar{k}_a = \frac{1}{m}\sum_{i=1}^{m} k_{ai} \tag{6}$$

The standard deviation σ_a of the axial static stiffness of the spindle unit's stiffness evaluation indices can reflect the degree of dispersion of its data. To express the data around $\bar{k}_a$ near the degree of density, the calculation formula is as follows:

$$\sigma_a = \sqrt{\frac{1}{m}\sum_{i=1}^{m}\left(k_{ai} - \bar{k}_a\right)^2} \tag{7}$$

The fluctuation is the degree of deviation in the measured value of the evaluation index of the spindle unit stiffness from the mathematical expectation in a statistical sense. The fluctuation of the evaluation index of the axial static stiffness a is calculated as follows:

$$B_a = \frac{\max\left(\left|\bar{k}_a - z\sigma_a - k_{a0}\right|, \left|\bar{k}_a + z\sigma_a - k_{a0}\right|\right)}{k_{a0}} \tag{8}$$

where z is the confidence interval of a normal distribution, and a 95% confidence interval (z = 1.96) can be selected in the consistency evaluation of the spindle unit stiffness. Analogously to the calculation process of the axial static stiffness fluctuation B_a, the spindle unit stiffness evaluation indices of the radial static stiffness and intrinsic frequency fluctuation can be obtained, as B_r and B_g.

The spindle unit stiffness fluctuation against consistency is shown in Table 1.

Table 1. Correspondence between fluctuation and consistency of spindle unit stiffness.

Level	Description	Fluctuation (*B*)
Grade A+	The spindle unit stiffness consistency is very good, considering the cost.	$B \leq 8.3\%$
Grade A	The consistency of the spindle unit stiffness is excellent and should be maintained.	$8.3\% < B \leq 10\%$
Grade B	The consistency of the spindle unit stiffness is good and should be improved as much as possible.	$10\% < B \leq 12.5\%$
Grade C	The consistency of the spindle unit stiffness is fair and should be improved as soon as possible.	$12.5\% < B \leq 16.7\%$
Grade D	The consistency of the spindle unit stiffness is poor and must be improved.	$16.7\% < B \leq 25\%$
Grade E	The consistency of the spindle unit stiffness is too poor to be acceptable and the process should be considered for modification.	$B > 25\%$

+ represents a higher grade.

3.2. Comprehensive Weights Assigned to Evaluation Indices

The spindle unit stiffness is an evaluation object that includes multiple evaluation indices, and there are two forms of consistency evaluation that synthesize multiple evaluation indices: one is to take the fluctuation of the group of evaluation indices with the largest fluctuation to indicate its consistency; the other is to apply the multi-index comprehensive weight assignment method to determine the weight and fluctuation of each evaluation index and to combine these to comprehensively evaluate its consistency.

Considering that the spindle unit stiffness contains many evaluation indices, it is biased to take only the group with the largest fluctuation to represent its fluctuation. Thus, this study adopts the multi-index comprehensive weight assignment method to evaluate its consistency. It combines the subjective and objective evaluation weights and analyzes the combined weight of the evaluation index's consistency to measure the spindle unit's stiffness consistency.

3.2.1. Subjective Weight Assignment

The first step of subjective weight assignment using the hierarchical method is to divide the target layer, criterion layer, and program layer. In the evaluation of the spindle unit's stiffness consistency, the target layer is the spindle unit stiffness; the criterion layer is the evaluation indices, including the radial static stiffness, axial static stiffness, and intrinsic frequency; and the program layer is the influencing factors affecting its evaluation indices. A sketch of the evaluation system for the stiffness of the spindle unit using the hierarchical method is shown in Figure 3.

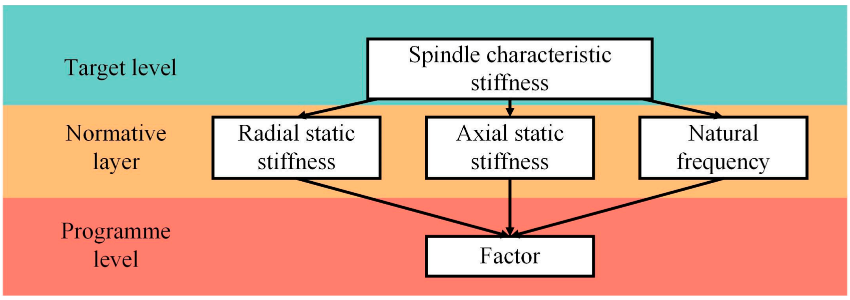

Figure 3. Hierarchical diagram of spindle unit stiffness evaluation system.

The second step in the hierarchical analysis is to construct a judgment matrix. Industry experts and scholars consider the spindle unit stiffness of each indicator to perform two-by-two comparisons of the scoring, describing the relative importance of the degree of access to the judgment matrix of its evaluation indicators.

The evaluation indices of the spindle unit stiffness are the axial static stiffness, radial static stiffness, and intrinsic frequency. Based on the expertise and experience of relevant experts, the evaluation indices of the spindle unit stiffness are scored by comparing the degrees of influence of the spindle unit two by two. This study invited senior engineers from machine tool manufacturers as industry experts to score the spindle unit stiffness evaluation indexes, so as to ensure the standardization of the scoring. The scoring range was 1–9, with larger scores indicating that the indicators in the relative rows are more important than those in the relative columns, and the scoring results of the spindle unit stiffness evaluation indicators are shown in Table 2 (s_{ra} indicates the result of scoring the importance of the radial static stiffness relative to the axial static stiffness, and the other designations can be seen by analogy with s_{ra}).

Table 2. Spindle unit stiffness characteristic judgment matrix.

Evaluation Index	Axial Static Stiffness	Radial Static Stiffness	Intrinsic Frequency
Axial static stiffness	1	s_{ar}	s_{ag}
Radial static stiffness	s_{ra}	1	s_{rg}
Intrinsic frequency	s_{ga}	s_{gr}	1

From Table 2, the judgment matrix A_s of the spindle unit stiffness evaluation index is as shown below:

$$A_s = \begin{bmatrix} 1 & s_{ar} & s_{ag} \\ s_{ra} & 1 & s_{rg} \\ s_{ga} & s_{gr} & 1 \end{bmatrix} \quad (9)$$

Calculate the weights of the spindle unit stiffness evaluation indices based on the judgment matrix of the evaluation indices.

1. Calculate the largest characteristic root λ^s_{max} and the corresponding eigenvector of the spindle unit stiffness judgment matrix A_s.

$$CI_s = \frac{\lambda^s_{\max} - n}{n - 1} \quad (10)$$

where n is the unique non-zero characteristic root.

2. Calculate the average random consistency index RI_z corresponding to the eigenvectors of the judgment matrix of the spindle unit stiffness (this can be obtained by consulting the standard tables).
3. Calculate the spindle unit stiffness judgment matrix eigenvector score consistency ratio CR_s

$$CR_s = \frac{CI_s}{RI_s} \quad (11)$$

If the result of the consistency test of the AHP evaluation score of the spindle unit stiffness is $CR_s < 0.1$, then the assignment of the AHP score is reasonable. The normalized spindle unit stiffness judgment matrix is summed in parallel to obtain the subjective weights of the spindle unit stiffness evaluation indices of the radial static stiffness, axial static stiffness, and intrinsic frequency, w_{or}, w_{oa}, and w_{og}.

3.2.2. Objective Weight Assignment

The CRITIC weight assignment method is adopted to carry out the objective weight calculation of the spindle unit stiffness evaluation index. The calculation process is as follows.

1. The evaluation matrix based on the spindle unit stiffness evaluation index data is constructed.

$$X = \begin{bmatrix} k_{r1} & k_{a1} & k_{g1} \\ k_{r2} & k_{a2} & k_{g2} \\ \vdots & \vdots & \vdots \\ k_{rm} & k_{am} & k_{gm} \end{bmatrix} \quad (12)$$

where X is the evaluation matrix of the spindle unit stiffness evaluation index; k_{ri}, k_{ai}, and k_{gi} represent the measured values of the spindle radial static stiffness, axial static stiffness, and intrinsic frequency, respectively.

2. The data normalization of the spindle unit stiffness evaluation indices is carried out. The evaluation indices of the spindle unit stiffness, axial static stiffness, radial static stiffness, and intrinsic frequency are all positive indices whose normalized formulas are as follows:

$$x'_{ij} = \frac{x_{ij} - \min(x)}{\max(x) - \min(x)} \quad (13)$$

where x'_{ij} is the normalized spindle unit stiffness evaluation index measurement data, x_{ij} is the spindle unit stiffness evaluation index measurement data, and x is the set of spindle unit stiffness evaluation index measurement data.

3. The variability of the evaluation index for the axial static stiffness is expressed in the form of a standard deviation σ_a
4. The conflicting nature of the evaluation index axial static stiffness is expressed in the form of correlation coefficients, with ${r_i}^a$ indicating the correlation coefficient between the evaluation index axial static stiffness a and a_i data.

$$R_a = \sum_{i=1}^{m} (1 - {r_i}^a) \quad (14)$$

5. The greater the information quantity C_a, the greater the degree of influence of the evaluation index axial static stiffness on the spindle unit stiffness, and greater weight should be assigned to it.

$$C_a = \sigma_a \sum_{i=1}^{m} (1 - {r_i}^a) = \sigma_a \times R_a \quad (15)$$

6. The expression for the objective weight w_{sa} of the evaluation index of the axial static stiffness is

$$w_{sa} = \frac{C_a}{\sum_{i=1}^{m} C_a} \quad (16)$$

Analogously to the calculation of the comprehensive weight w_{sa} of the spindle unit's axial static stiffness, one can obtain the comprehensive weights of the spindle unit's radial static stiffness and intrinsic frequency, w_{sr} and w_{sg}.

4. Experimental Verification of Spindle Unit Stiffness Consistency Evaluation

4.1. Spindle Unit Stiffness Test

4.1.1. Static Stiffness Test

This study considers the detection of the radial static stiffness and axial static stiffness of seven spindles of a certain type of lathe. The spindle's static stiffness testing process is as follows.

The spindle unit is fixed to the platform by fixing the jacket of the spindle through the combination of a pressure plate and a V-block; the loading device connects the platform and the front end of the spindle based on an L-bracket (the pads are used for radial loading) and the loading of the spindle is realized through the rotation of the bolts; a micrometer detects the deformation of the front end of the spindle based on the support of the gauge holder in the relative direction of the loading force (the axial static stiffness test is performed in the same direction as the loading force); the loading force can be measured by pressure sensing in the loading device. Based on the above constraints and detection conditions, the deformation of the front end of the spindle is detected for gradual loading (0~2000 N, with the load increasing by 500 N each time) and gradual unloading (2000~0 N, with the load decreasing by 500 N each time), and two sets of data corresponding to the deformation of the front end of the spindle can be obtained for the same load. Moreover, the average of the two sets of data is taken as the deformation of the front end of the spindle for the corresponding loading conditions. The static stiffness of the spindle unit is the ratio of the loading force and deformation, and the average value of the stiffness under different loading force conditions is taken as the result of its stiffness test.

The experimental diagram of the seven-spindle static stiffness test of a certain type of lathe is shown in Figure 4, and the test results are shown in Table 3.

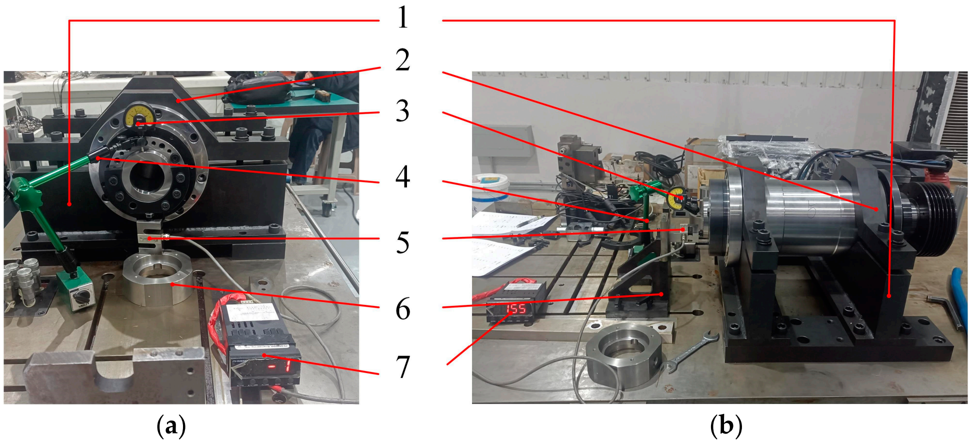

Figure 4. Experimental diagram of spindle static stiffness detection: (**a**) radial static stiffness; (**b**) axial static stiffness. 1. V-block, 2. Plate, 3. Micrometer, 4. Gauge holder, 5. Force transducer, 6. L-bracket (pads), 7. Load force monitor.

Table 3. Spindle unit stiffness evaluation index experimental measurement data.

No.	Radial Static Stiffness (N/µm)	Axial Static Stiffness (N/µm)	Intrinsic Frequency (Hz)
1	450.79	611.11	650
2	475.31	539.68	636.3
3	466.67	577.78	655
4	484.13	611.11	663.8
5	539.68	666.67	660
6	500.00	650.79	637
7	466.67	595.24	635.5
Target value	483	607	648

4.1.2. Intrinsic Frequency Detection

Next, this study considers the detection of the first-order intrinsic frequencies of seven spindles of a certain type of lathe. The spindle's intrinsic frequency detection process is as follows.

The spindle unit is restrained by means of slings and rings, which ensure that the spindle is in a freely restrained state; vibration sensors are installed at the response point (front bearing parts) to collect the spindle's vibration signals at the time of impact, using the force hammer at the excitation point (rear bearing parts) to apply impact. Through the head of the hammer, the impacts of the force sensors are collected; the sensor signal is then sent to the processor and uploaded to the host computer, based on the PULSE system, to obtain the frequency response curve of the spindle. The curve is analyzed to obtain the spindle's intrinsic frequency.

The experimental diagram for the detection of the intrinsic frequencies of seven spindles of a certain type of lathe is shown in Figure 5, and the detection results are shown in Table 3.

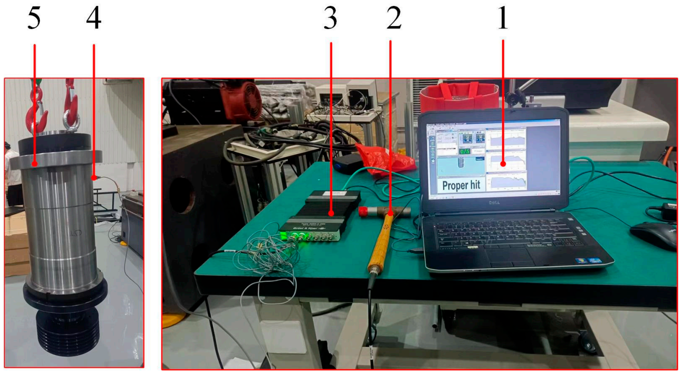

Figure 5. Experimental study of spindle intrinsic frequency. 1. Host computer, 2. Force hammer, 3. Processor, 4. Vibration sensor, 5. Spindle.

4.2. Consistency Evaluation of Spindle Unit Stiffness

Based on the spindle unit stiffness consistency evaluation method and the seven-spindle stiffness experimental testing data of a certain type of lathe, a consistency evaluation analysis is performed. The spindle unit stiffness evaluation index experimental test data for a certain type of lathe are shown in Table 3.

1. Based on Equations (9)–(11), the fluctuations B_r, B_a, and B_g of each evaluation index are calculated and the results are shown in Table 4.

Table 4. Results of the evaluation of the fluctuations of the evaluation indices.

Evaluation Index	Radial Static Stiffness	Axial Static Stiffness	Intrinsic Frequency
Fluctuation	11.06%	12.90%	3.39%

As can be seen from Table 4, the consistency of the radial static stiffness in the spindle unit's stiffness evaluation index is good, located within the B level, but still needs to be improved; the consistency of the axial static stiffness in the spindle unit's stiffness evaluation index is general, located within the C level, and needs to be improved; the consistency of the intrinsic frequency in the spindle unit's stiffness evaluation index is very good, located within the A+ level, which can be considered to reduce the cost. From the aforementioned results, it can be found that, for the same batch of spindle units, the consistency level of the stiffness evaluation indices varies. Therefore, the use of the consistency level of one evaluation index, the spindle unit stiffness, to represent its consistency level causes bias.

2. Based on the subjective weight assignment method using the three spindle unit stiffness evaluation indices for subjective assignment, the evaluation indices in terms of the score comparison table and the subjective assignment results are as shown in Table 5 and Figure 6.

Table 5. Judgment matrix of spindle unit stiffness evaluation indices.

Evaluation Index	Axial Static Stiffness	Radial Static Stiffness	Intrinsic Frequency
Axial static stiffness	1	1/4	3
Radial static stiffness	4	1	6
Intrinsic frequency	1/3	1/6	1

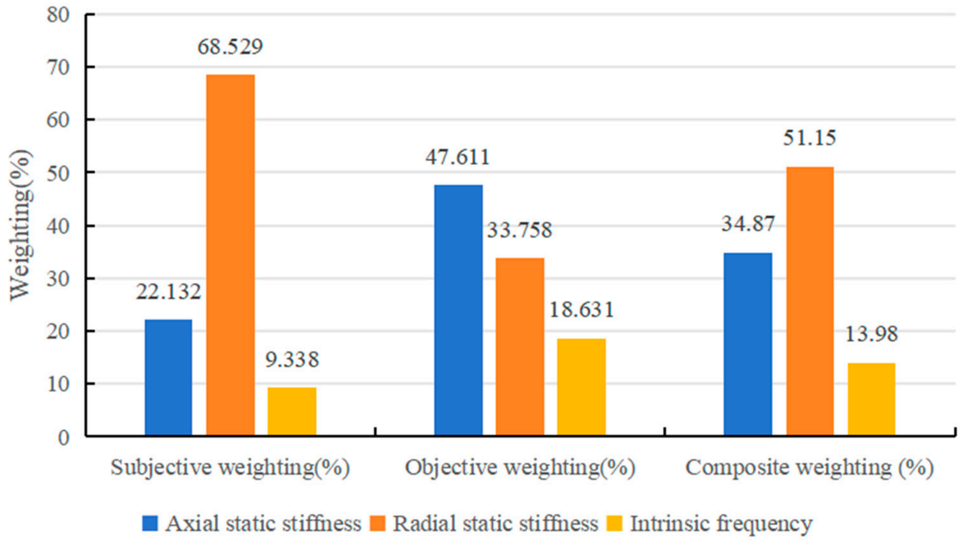

Figure 6. Weights of spindle unit stiffness assessment indicators.

The result of the AHP evaluation score consistency test for the spindle unit stiffness $CR_s = 0.027 < 0.1$, and the AHP score assignment is reasonable. The subjective weights w_{or}, w_{oa}, and w_{og} of the spindle unit stiffness evaluation indices were obtained, as shown in Figure 6.

3. Based on the objective weight assignment method for the three spindle unit stiffness evaluation indices using objective assignment via Equations (12)–(16), the calculation of the spindle evaluation indices regarding the objective assignment results w_{sr}, w_{sa}, and w_{sg} can be performed, as shown in Figure 6.
4. Based on the linear weighting method using Equation (5), the subjective and objective weights of the spindle unit stiffness evaluation indices are synthesized to obtain the comprehensive weighting results w_r, w_a, and w_g of the evaluation indices, as shown in Figure 6.
5. The fluctuation and the comprehensive weight of the single evaluation index of the spindle unit stiffness are substituted into Equation (4), and the fluctuation B_z can be obtained as 10.63%. The stiffness consistency of the spindle units in this group is located within level B. Its consistency is good, but it still needs to be improved and optimized.

Through the evaluation of the consistency of the spindle unit stiffness of a certain type of lathe, the feasibility of the spindle unit stiffness consistency evaluation method proposed in this paper has been verified. It is scientific and reasonable, with simplicity and operational applicability.

5. Discussion and Recommendations

In this paper, the consistency of the spindle unit stiffness, as a multi-index evaluation object, is divided into two parts for evaluation: one part is used to evaluate the consistency of the single evaluation index, and the other part is used to obtain the comprehensive weight of its evaluation index relative to it. The consistency of the spindle unit stiffness is obtained by combining the consistency of its individual evaluation indices with the combined weights. Analogous to the principle of the consistency evaluation of the spindle unit stiffness, based on this method, it is possible to evaluate the consistency of multiple indicators of spindle unit properties of the same data type. This paper expresses the level of consistency through the fluctuation degree, but other methods can also be used to express the consistency, such as the ICC intra-group correlation coefficient, Kappa test coefficient, and Kendall coefficient, which can be chosen according to the characteristics of different evaluation objects.

Based on the characteristics of the spindle unit stiffness consistency evaluation method in this paper, the rules to be followed in evaluating the stiffness consistency of a group of spindle units in the actual production environment are summarized as follows.

1. Selection of evaluation indices. The actual application characteristics of different spindles determine differences in their indices of concern. Based on the different processing requirements, it is necessary to select the actual spindle unit stiffness of the index as the consistency evaluation index. The low-speed, heavy-duty conditions of the spindle can be removed as appropriate dynamic-stiffness-related indices, to ensure the accuracy of the evaluation based on the premise of alleviating the difficulty of experimental testing.
2. Selection of data volume. As the consistency of the spindle unit stiffness expresses the degree of dispersion of the spindle unit stiffness of a batch of spindles, the number of spindles for which raw data are collected should not be less than five.
3. Specifications of data detection. As the consistency of the spindle unit stiffness is generally used to express the consistency of the same type and batch of spindles, the fluctuation of the data is limited. In order to prevent the evaluation results from being too large, the uniformity of the experimental testing process of the data should be strictly controlled to reduce the generation of errors and guarantee the accuracy of the consistency evaluation.

6. Conclusions

This paper proposes a method for the evaluation of the spindle unit stiffness consistency, which enables the evaluation of the level of performance consistency of spindle units with the same data type.

1. Addressing the situation whereby the spindle unit stiffness contains multiple evaluation indices, a multi-index comprehensive weighting model is established. The multi-index comprehensive weighting model takes into account the subjective and objective weights of the evaluation indices, which makes the weighting results more comprehensive and reasonable. Based on the comprehensive weights of the spindle unit stiffness evaluation indices, the fluctuations of its evaluation indices are weighted and summed to obtain its comprehensive consistency level.
2. Based on a set of experimental data on the spindle unit stiffness, the statistical fluctuation method is applied to obtain the fluctuation of its evaluation indices, and the multi-index comprehensive weight assignment model is applied to obtain the comprehensive weight of its evaluation indices. Finally, the consistency level of the stiffness of a group of spindle units is obtained by the weighted summation of the fluctuations of their evaluation indices. The spindle unit stiffness consistency level of this group is the B level, which is in accordance with the grade range of factory products. The B level indicates that the group of spindle units' stiffness consistency is good, but there is still room for improvement. The evaluation of the spindle unit's stiffness consistency for this group verifies the feasibility of the spindle unit stiffness consistency evaluation method.
3. In summary, the spindle performance consistency evaluation, aiming to follow the general evaluation rules, should be based on different machines' spindle unit stiffness characteristics, focusing on the flexible selection of the evaluation index, determining the number of evaluations, and so on, to provide a unified method for the evaluation of the spindle unit's performance consistency.

In the future, our primary task is to increase the application of the spindle unit stiffness consistency evaluation method, in order to more comprehensively verify the value of the evaluation method in actual production and processing and to identify the defects in the evaluation method. Our next step is to cooperate with a machine tool factory to carry out the evaluation of the spindle unit stiffness consistency in the spindle unit product inspection process, as well as to collect user feedback to analyze the comprehensive impact of the spindle unit's stiffness consistency on the user experience. We will also analyze the factors affecting the spindle unit's stiffness consistency, adjust the spindle unit parts' processing and assembly standards, and try to control the spindle unit's stiffness consistency.

Author Contributions: Supervision, writing—review and editing, F.S.; writing—original draft preparation, methodology, validation, formal analysis, data processing, Y.J.; funding acquisition, project administration, R.Z. and Q.Z.; supervision, F.X., C.Z. and H.Z.; resources, W.Y., B.L. and S.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research is supported by the National Natural Science Fund of China, grant number 52375258; the China Postdoctoral Science Foundation, grant number 2022M722223; the Scientific Research Fund Project of Liaoning Provincial Department of Education, grant number JYTMS20231191; the Major Project of the Ministry of Science and Technology of Liaoning Province, grant number 2022JH1/10400027; and the Key Project of the Ministry of Science and Technology of Liaoning Province, grant number 2022JH1/10800081.

Data Availability Statement: The data are contained within the article.

Acknowledgments: We thank L.Z. (Liang Zhang) for their suggestions and recommendations.

Conflicts of Interest: Authors Wenhua Yang, Bo Li and Shuang Bai were employed by the company Genertec Shenyang Machine Tool Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Matsubara, A.; Tsujimoto, S.; Kono, D. Evaluation of dynamic stiffness of machine tool spindle by non-contact excitation tests. *Cirp. Annals* **2015**, *64*, 365–368. [CrossRef]
2. Ma, C. An Innovative Process Design Model for Machined Surface Error Distribution Consistency in High-Efficiency Milling. *Appl. Sci.* **2022**, *12*, 7199. [CrossRef]
3. Wei, Y.; Hu, T.; Zhou, T.; Ye, Y.X.; Luo, W.C. Consistency retention method for CNC machine tool digital twin model. *J. Manuf. Syst.* **2020**, *6*, 313–322. [CrossRef]
4. Raplee, J.; Gockel, J.; List, F.; Carver, K.; Babu, S.S. Towards process consistency and in-situ evaluation of porosity during laser powder bed additive manufacturing. *Sci. Technol. Weld. Join.* **2020**, *8*, 679–689. [CrossRef]
5. Ermakov, M. On uniform consistency of nonparametric tests. II. *J. Math. Sci.* **2021**, *6*, 629–642. [CrossRef]
6. Shen, P.C.; Jia, S.H.; Yang, H.J.; Chang, Y.; Chen, H.L.; Mei, X.S. Research on the consistency of Y-axis motion straightness of vertical machining center based on SVR-KM algorithm. *Mod. Manuf. Eng.* **2019**, *11*, 79–84.
7. Jiang, T.Q.; Jia, S.H.; Li, D.Y.; Song, X.B.; Guo, K.; Chen, H.L.; Mei, X.S. A study on the machining consistency of straightness of the main rail of the bed of a certain type of machine tool. *Mach. Tools Hydraul.* **2019**, *3*, 187–191.
8. Li, D.D.; Wang, J.J.; Zhao, Q.Z.; Bian, Y.G.; Cui, Y.J.; Hu, Y. Research on consistency evaluation method of CNC machine tool machining. *Manuf. Technol. Mach. Tools* **2023**, *11*, 116–122. [CrossRef]
9. Yanlong, G.; Xingmeng, M.; Linfu, Z. Comprehensive evaluation of the quality of rural habitat environment in huizhou cultural and ecological protection zone. *Pol. J. Environ. Stud.* **2024**, *3*, 2077–2092.
10. Zeng, W.H.; Rao, Y.Q.; Wang, P.; Yi, W.H. A solution of worst-case tolerance analysis for partial parallel chains based on the Unified Jacobian-Torsor model. *Precis. Eng.* **2017**, *9*, 276–291. [CrossRef]
11. Han, W.; Yang, Z.Q.; Huang, L.D.; Sun, C.X.; Yu, X.J.; Zhao, M.F. Fuzzy comprehensive evaluation of the effects of relative air humidity on the morpho-physiological traits of Pakchoi (*Brassica chinensis* L.) under high temperature. *Sci. Hortic.* **2019**, *11*, 246. [CrossRef]
12. Jing, L.; Min, Q.; Li, W.H.; Bai, Y.; Yang, L. Evaluation of water resources conserved by forests in the Hani rice terraces system of Honghe County, Yunnan, China: An application of the fuzzy comprehensive evaluation model. *J. Mt. Sci.* **2016**, *4*, 744–753.
13. Sun, H.Y.; Wang, S.F.; Hao, X.M. An Improved Analytic Hierarchy Process Method for the evaluation of agricultural water management in irrigation districts of north China. *Agric. Water Manag.* **2016**, *8*, 179. [CrossRef]
14. Wang, W.; Li, Q.C.; Kang, W.J.; Tao, W.J.; Du, L. Evaluation of machining performance and error traceability method for five-axis CNC machine tools based on comprehensive evaluation system. *J. Mech. Eng.* **2017**, *5*, 149–157. [CrossRef]
15. Wu, T.; Wen, M. An English teaching ability assessment method based on fuzzy mean-shift clustering. *Sci. Program.* **2022**, *2022*, 4219249. [CrossRef]
16. Stoumbos, Z.G. Process capability indices: Overview and extensions. *Nonlinear Anal. Real World Appl.* **2002**, *2*, 191–210. [CrossRef]