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MECHANICAL AND AERONAUTICAL ENGINEERING, THERMODYNAMICS

A new modeling and evaluation method of all stages of inherent energy consumption for the spindle system

Xiaolei DENG[1], **Xuanyi WANG**[2], **Weiwei GAO**[3], **Yahao CHEN**[2], **Honglie MA**[1],
Xiaoliang LIN[3*], and **Huan LIN**[3]

[1] College of Mechanical Engineering, Jiaxing University, Jiaxing 314001, China
[2] College of Mechanical Engineering, Zhejiang University of Technology, Hangzhou 310032, China
[2] Key Laboratory of Intelligent Manufacturing for Aerodynamic Equipment of Zhejiang Province, Quzhou University, Quzhou 324000, China

Abstract. Against the backdrop of green transformation and energy efficiency improvement in the manufacturing industry, machine tools, as the core equipment of industrial production, have become a key element in reducing industrial carbon emissions through energy optimization. The spindle system, as the core component of a machine tool, accounts for 40%–60% of the total energy consumption during the cutting process. However, existing research mostly focuses on energy consumption during the cutting stage and lacks systematic modeling and quantitative evaluation of the inherent energy consumption characteristics for the spindle throughout the entire stage (standby, start-up, idle, and braking). This article proposes a modeling method that fills that gap. Using experimental data, we created energy consumption functions for each stage and established an evaluation system that included indicators such as standby power, expected idle power, and mass energy ratio. We conducted a validation study on the effectiveness of the model and the practicality of evaluation indicators for two vertical machining centers, VMC1165H and VMC855H. The results indicate that the research findings can provide a quantitative basis for optimizing machine tool design and energy-saving regulation of process parameters and help improve energy efficiency and low-carbon transformation in the manufacturing industry.

Keywords: spindle system; energy consumption analysis; energy consumption characteristics; evaluation system; machine tool; green manufacturing.

1. INTRODUCTION

The comprehensive implementation of green manufacturing has led to profound changes in intelligent green manufacturing industries, such as smart equipment and smart factories [1–3]. The processing equipment, i.e., machine tools used in the manufacturing process, accounts for a substantial proportion of the total energy consumption [4], but the energy efficiency utilization rate is usually below 30% [5,6]. Numerical control machine tools have the characteristics of a complex structure and wide application. Because machine tools have substantial room to improve their energy efficiency, they offer enormous energy-saving potential. Energy efficiency rating evaluation provides the foundation for achieving energy conservation in machine tools and serves as a prerequisite for energy efficiency optimization [7,8].

As a key component of machine tools, the spindle system accounts for more than 15% of the total energy consumption of the entire machine process [9]. The inherent energy consumption of the spindle system serves as an indicator of the energy efficiency of the spindle itself, which is closely related to the average energy-efficiency level of the entire machine tool processing [10]. Therefore, it is crucial to conduct systematic modeling and quantitative evaluation research on the inherent energy consumption characteristics of the spindle system throughout its lifecycle, and it has also become a research hotspot for scholars at home and abroad. Recently, Huang *et al.* [11] proposed a method for determining start-up energy consumption using a specific database composed of data and functions, with an error rate of only 2.97%. Lv *et al.* [12] developed a model for predicting the ESA of CNC machine tools based on the principles of spindle mechanical transmission and motor control, with an error within 6%. Pawanr *et al.* [13] developed an empirical model to predict the energy consumption of machine tools under transient conditions, with R^2 values consistently above 99%. Jia *et al.* [14, 15] proposed a finite state machine-based transient energy consumption modeling method for machining, which has higher prediction accuracy compared to prediction models without transient energy. They also proposed an energy demand modeling method for key state transitions in turning processes, with the prediction accuracy of the proposed method usually above 90%.

During mechanical processing, the energy efficiency indicators of machine tools play a crucial role in determining the energy consumption and efficiency of the processing. As a result, this topic has attracted great interest from researchers. Tuo *et al.* [10] analyzed the connotation of intrinsic energy efficiency of

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[*] e-mail: lxl@qzc.edu.cn

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machine tools and proposed a virtual workpiece method to effectively describe the intrinsic energy efficiency of machine tools, leading to the evaluation of the intrinsic energy efficiency of machine tools. Ma *et al.* [16] adopted the PSO-SVM model and created an energy efficiency evaluation index system for machine tool systems based on three aspects: motor load characteristics, energy efficiency processing, and power quality. The evaluation grading method of this system can effectively reflect the real-time energy efficiency of machine tools. Cui *et al.* [17] proposed a method for evaluating machine-tool energy-efficiency ratings using a self-organizing map followed by K-means clustering, enabling the classification of machine tool energy efficiency ratings. Wang *et al.* [18] used the Analytic Hierarchy Process to determine the weight factors of seven evaluation indicators in specific scenarios and the weight factors of eight energy efficiency testing methods under each evaluation indicator and verified the effectiveness and accuracy of the evaluation results through consistency testing. Ma *et al.* [19] proposed a new energy efficiency rating evaluation method based on intrinsic energy efficiency, which not only evaluates the energy efficiency rating of machine tools but also reveals their high energy efficiency range.

In addition to the energy efficiency of the spindle system and the machine tool system itself, the energy consumption and thermal control of machine tools during machining have also attracted extensive attention. Lai *et al.* [20] established a cutting energy efficiency model that considers the coupled relationship between material removal and machining accuracy in thermal control, and proposed a thermal control energy consumption ratio index to characterize its impact on total energy consumption, revealing the coupled effects of material removal and thermal control on energy efficiency and machining accuracy. In another study focusing on dry cutting machine tools, Lai *et al.* [21] introduced exergy analysis to address thermal issues in the cutting space and proposed an effective energy time-varying graphical method to evaluate the thermal energy efficiency of the cutting space. This method can serve as an effective tool for evaluating the thermal energy efficiency of machine tool cutting spaces, assisting designers and users in identifying inefficient links in the machine tool thermodynamic process and thereby improving overall environmental performance. Liu *et al.* [22] established an analytical static stiffness model for the entire machining workspace and constructed a machining energy model to quantify the load level of machine tools based on the requirements of lightweight and balanced machining motion components. Energy efficiency evaluation was conducted using the TOPSIS method, providing a quantitative basis for the configuration optimization of machine tools. Naumann *et al.* [23] reviewed existing compensation strategies and evaluated their impact on energy consumption, including methods to reduce thermal losses, decrease the sensitivity of tool center points to thermal effects, cooling strategies, air conditioning, controllable heat transfer methods, and various calculation methods for predicting and correcting thermal positioning errors. Can *et al.* [24] proposed a practical method for achieving closed-loop energy demand optimization in milling machines for mass production, including the use of edge devices to interconnect machine tools and verify production target concepts. This method was implemented on a grinding machine in camshaft production, saving approximately 12% of energy without changing the overall equipment efficiency. Hu *et al.* [25] proposed a machine tool energy index system including component division, state identification, energy monitoring, energy consumption modeling, energy index selection, energy index calculation, and energy index application, and based on top-down and bottom-up energy modeling methods. This research provides important guidance for machine tool manufacturers, distributors, and processing workshops that aim to achieve energy savings during production.

The above research findings show that there are two limitations in existing studies: firstly, energy consumption analysis mostly focuses on the cutting stage, and insufficient attention is paid to non-cutting stages, such as start-up, braking, and idle, resulting in one-sided energy consumption evaluation. Secondly, evaluation indicators often rely on a single parameter (such as idle power), lacking quantitative indicators that can comprehensively reflect the matching degree between spindle quality and energy consumption, making it difficult to optimize the design and improve the process. Based on this, this article presents a full-stage inherent energy consumption model for the spindle system, covering four key stages: standby, start-up, idle, and braking (as cutting energy consumption is mainly affected by machining parameters and is not closely related to the spindle performance, it is not considered). The energy consumption function is established through experimental data fitting and probability statistical methods. Simultaneously, an evaluation index system is proposed that includes power expectation, energy consumption expectation, quality-to-energy ratio, etc., and its effectiveness is verified through case studies.

2. MODELING OF INHERENT ENERGY CONSUMPTION THROUGHOUT THE ENTIRE STAGE OF THE SPINDLE SYSTEM

2.1. Analysis of spindle energy consumption

The energy consumption of a machine tool is complex. Figure 1 shows a typical power curve of the machine tool, which can be divided into four stages: standby, start-up, idle, and braking.

(1) Standby phase: After the machine tool is powered on, the spindle does not start, and only the electrical control system, lighting, and other components operate. The power is stable, but the duration is long, ensuring the stable operation of the machine tool. Accumulated energy consumption cannot be ignored.

(2) Start-up phase: The spindle accelerates from a standstill to the target speed, which is a transient phase between standby and idle. At this stage, it is necessary to overcome the static inertia of the spindle motor and transmission system, so a sudden increase in power in a brief period will produce power spikes, which will significantly increase with an increase in the target speed.

(3) Idle stage: The spindle maintains a stable speed, but no cutting load, and the power is positively correlated with the speed. This stage is the main energy source during the continuous machining gap period.

(4) Braking stage: The spindle decelerates from the target speed to a standstill, which is a transient stage between idle and standby. During this stage, the machine tool uses feedback brakes to rapidly reduce power, resulting in a power peak opposite to the start-up stage. Its energy consumption characteristics are related to braking time and speed.

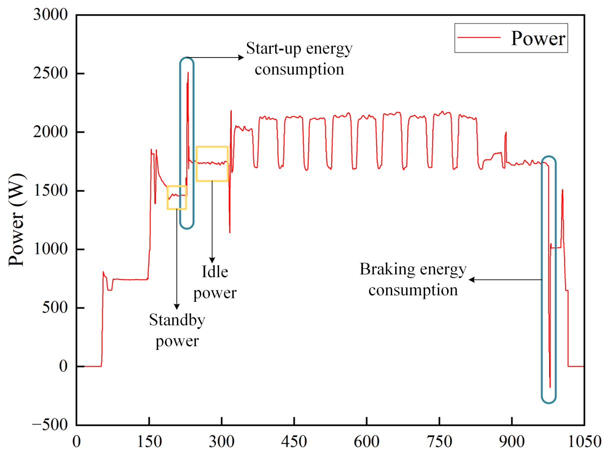


Fig. 1. Machine tool power diagram

2.2. Modeling of inherent energy consumption

The modeling of inherent energy consumption in the entire stage of the spindle system needs to be achieved through three steps: experimental data acquisition, stage feature extraction, and function fitting, as follows:

(1) Experimental data collection: The experimental data of the machine tool were collected using a power meter, and the resulting data line graph is shown in Fig. 2.

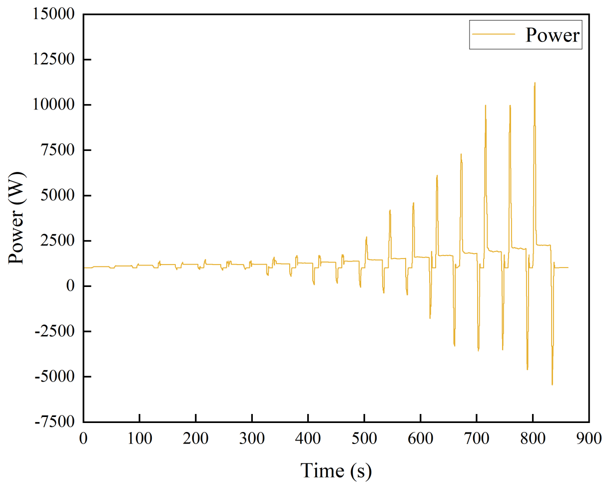


Fig. 2. Experimental data collection diagram

(2) Stage feature extraction: The power of the spindle system is usually constant during the standby and idle stages, and the corresponding data can be obtained by taking the average value over a period. However, the power will vary during the start-up and braking stages, so it needs to be considered separately. The power distribution during the start-up phase of the spindle system is shown in Fig. 3. To determine the starting and ending points of the spindle system start-up phase, the paper [11] proposes that the start-up phase begins when the power percentage between every two consecutive points increases by 100%, i.e., E_{s-s} in the figure. When the power percentage between two consecutive points is less than 10%, the start-up phase ends, i.e., E_{s-e} in the figure. The power distribution diagram during the braking phase of the spindle system is shown in Fig. 4. Similarly, to determine the starting and ending points of the braking phase of the spindle system, the braking phase begins when the power percentage between every two consecutive points increases by 100%, which is represented by E_{e-s} in the figure. When the change of power percentage between two consecutive points is less than 10%, the braking phase ends, which is represented by E_{e-e} in the figure.

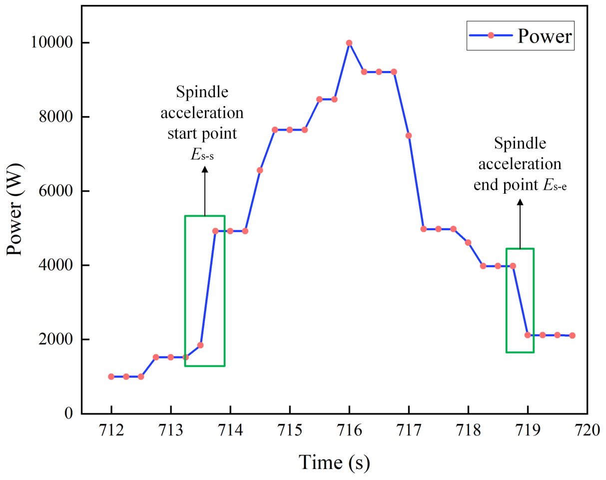


Fig. 3. Start-up energy consumption data

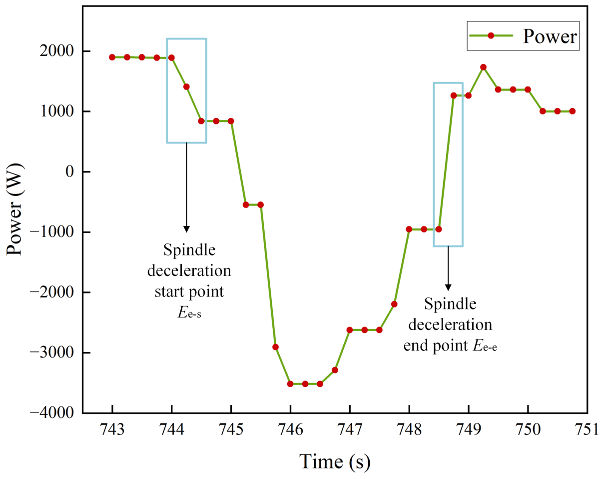


Fig. 4. Braking energy consumption data

(3) Function fitting: In order to record the inherent energy consumption (including start-up, idle, and braking) of the spindle system of a CNC machine tool at different selected speeds, an

empirical regression model can be established to predict the relationship between the inherent energy consumption and speed of the spindle at all stages, which can be expressed as:

$$E(n) = A + Bn + Cn^2 + Dn^3, \tag{1}$$

where $E(n)$ is the inherent energy consumption of the entire stage; n is the rotational speed, and A, B, C, and D are the fitting coefficients.

3. EVALUATION INDICATORS AND ACQUISITION METHODS FOR SPINDLE SYSTEM

In the machining process, the energy consumption increment of CNC machine tools comes from the spindle system, and the energy consumption generated by the spindle system during start-up, idle, and braking will vary with the change of speed. To comprehensively evaluate the energy consumption generated by the operation of the CNC machine tool spindle system, the energy consumption expectation corresponding to the spindle speed is adopted as the energy consumption index of the machine tool operating state. This article uses a normal distribution to characterize the probability of using the spindle speed of CNC machine tools with the change of speed:

$$f(n) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{(n-\mu)^2}{2\sigma^2}}, \tag{2}$$

where $f(n)$ is the probability of the corresponding rotational speed n, $\mu = \dfrac{(n_{\min} + n_{\max})}{2}$, $\sigma = \dfrac{(n_{\max} - n_{\min})}{6}$, $n_{\min}$ is the minimum speed of the spindle system, and $n_{\max}$ is the maximum speed of the spindle system.

In the actual production and processing of general mechanical parts, the spindle speed of CNC machine tools is usually set in the medium speed range to balance machining efficiency, machining accuracy, and tool life. The normal distribution with a mean of $\dfrac{(n_{\min} + n_{\max})}{2}$ can well fit the actual usage pattern of spindle speed in most conventional machining scenarios, and is a widely used probability distribution model in energy consumption research in the manufacturing field, possessing sufficient statistical rationality. For special machining scenarios such as high-speed precision machining and low-speed heavy cutting, the probability distribution of spindle speed is more consistent with skewed distributions such as the lognormal distribution and the Weibull distribution. The model of energy consumption expectation proposed in this paper can be extended by replacing it with the corresponding non-normal distribution function, and the calculation method of the energy consumption expectation index remains unchanged, exhibiting good scalability.

(1) Standby power: Machine tool standby power refers to the power of the machine tool during the period from the start of the main power supply, electrical control system, auxiliary system, etc., to the start of the main motor. The standby power reflects the basic energy consumption requirements of the machine tool, and the calculation formula is as follows:

$$E_{\mathrm{sb}} = \frac{\sum\limits_{i=1}^{m} P_{\mathrm{sb},i}}{t}, \tag{3}$$

where E_{sb} is the standby energy consumption; $P_{\mathrm{sb},i}$ is the real-time power value measured when the machine tool is in standby mode; t is the collected power count.

(2) Idle power expectation: Based on the probability of using each speed of the machine tool, the probability of using each speed of the CNC machine tool spindle and its corresponding idle power are integrated to obtain a comprehensive measurement of the idle power value of the machine tool spindle, which is called the idle power expectation. The calculation formula is as follows:

$$E_{\mathrm{e,u}} = \int P_{\mathrm{u}}(n) \times f(n)\,\mathrm{d}n, \tag{4}$$

where $E_{\mathrm{e,u}}$ is the expected idle power of the spindle; $P_{\mathrm{u}}(n)$ is the idle power value corresponding to the spindle when the speed is n.

(3) Start-up energy consumption expectation: Based on the probability of using each speed of the machine tool, the probability of using each speed of the CNC machine tool spindle and its corresponding start-up energy consumption are integrated to obtain a comprehensive measure of the energy consumption value for starting the machine tool spindle, which is called the start-up energy consumption expectation. The calculation formula is as follows:

$$E_{\mathrm{e,st}} = \int E_{\mathrm{st}}(n) \times f(n)\,\mathrm{d}n, \tag{5}$$

where $E_{\mathrm{e,st}}$ is the expected start-up energy consumption of the spindle; $E_{\mathrm{st}}(n)$ is the start-up energy consumption value corresponding to the spindle when the speed is n.

(4) Braking energy consumption expectation: Based on the probability of using each speed of the machine tool, the probability of using each speed of the CNC machine tool spindle and its corresponding braking energy consumption are integrated to obtain a comprehensive measure of the energy consumption of the machine tool spindle braking, which is called the braking energy consumption expectation. The calculation formula is as follows:

$$E_{\mathrm{e,bk}} = \int E_{\mathrm{bk}}(n) \times f(n)\,\mathrm{d}n, \tag{6}$$

where $E_{\mathrm{e,bk}}$ is the expected braking energy consumption of the spindle; $E_{\mathrm{bk}}(n)$ is the braking energy consumption value corresponding to the spindle when the speed is n.

(5) Inherent mass to energy ratio of spindle system: Intrinsic mass to energy ratio of spindle system is an empirical indicator used in engineering practice to measure the correlation between spindle system and quality characteristics. It can provide a quantitative basis for design optimization (such as lightweighting, low inertia) or process improvement (such as parameter optimization, tool upgrading). The lower the value of this indicator,

the lower the energy consumption per unit mass of the spindle system under the same operating conditions. This indicates that the design of the spindle structure and material selection are more reasonable, achieving a match between lightweight and low energy consumption. At the same time, the dynamic performance of the spindle is better, resulting in less energy loss caused by its own mass characteristics during startup, braking, and idling phases. The inherent mass energy ratio of the spindle system can be considered from the aspects of standby energy consumption, start-up energy consumption, idle energy consumption, and braking energy consumption. The calculation formula is as follows:

$$E_{\mathrm{ef}} = \frac{(E_{\mathrm{e,st}} - E_{\mathrm{sb}}) + (E_{\mathrm{e,u}} - E_{\mathrm{sb}}) + (E_{\mathrm{e,bk}} - E_{\mathrm{sb}})}{m}, \tag{7}$$

where E_{ef} is the inherent specific energy efficiency of the spindle system; E_{sb} is the total standby energy consumption; m is the spindle mass.

4. CASE STUDY

4.1. Experimental purpose and experimental setup

This article conducts energy consumption experiments on the spindle system of the vertical machining center VMC1165H developed by a certain machine tool factory. The experimental platform is built as shown in Fig. 5. The power analyzer used in this process is the AWS2103 produced by Aitek company, with a sampling interval of 250 ms. In the three-phase four-wire link mode, three current clamps and four voltage lines are used to capture voltage signals, current signals, and power factors. Power information is processed by the analyzer to explain the power test plan and the layout of the test instruments.

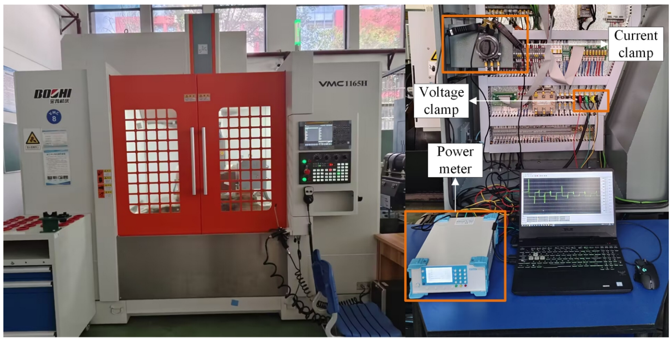


Fig. 5. VMC1165H power measurement test platform

In the power experiment, the spindle idle speed range was set to 0–10 000 r/min, and data collection was conducted at an interval speed of 500 r/min. Each group completes 20 sets of data collection in a start-up cycle, idle for 30 seconds, braking, and standby for 10 seconds. The resulting line graph is shown in Fig. 2. When calculating the energy consumption of spindle start-up, idle power, and braking energy consumption, it is necessary to subtract the standby power of the machine tool from the measured values and take the average value. The results are shown in Table 1.

Table 1
Inherent energy consumption of the VMC1165H spindle system in all stages

Speed (r/min)	Start-up energy consumption (J)	Braking energy consumption (J)	Idle power (W)
500	59.2	102.7	62.0
1000	331.5	148.4	102.1
1500	650.3	199.4	141.2
2000	1212.1	573.9	178.4
2500	1056.4	746.4	193.1
3000	1451.5	852.6	187.7
3500	1495.4	697.8	183.7
4000	1481.4	1784.4	200.1
4500	2314.8	2123.8	228.2
5000	2491.0	3577.6	265.2
5500	2527.8	3453.3	317.6
6000	2850.0	4528.6	371.4
6500	5662.3	5457.2	442.1
7000	10151.8	6673.5	513.0
7500	11345.6	7357.8	592.9
8000	17620.7	16204.2	688.2
8500	21922.9	18088.5	809.2
9000	31068.4	16733.2	915.0
9500	32350.9	21196.4	1072.2
10000	35092.9	26385.3	1250.7

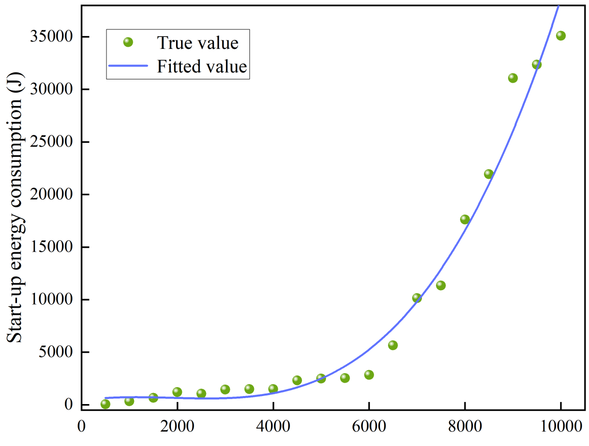
4.2. Experimental results

The data of VMC1165H vertical machining center was organized, and a cubic polynomial (1) was used to fit the functions of start-up energy consumption, idle power, and braking energy consumption to predict the relationship between the inherent energy consumption and speed of the CNC machine spindle in all stages. The obtained function fitting graph is shown in Fig. 6, and the fitting function model and its R^2 results are shown in Table 2. From the fitting results, all three energy consumption models of VMC1165H exhibit extremely high fitting accuracy:

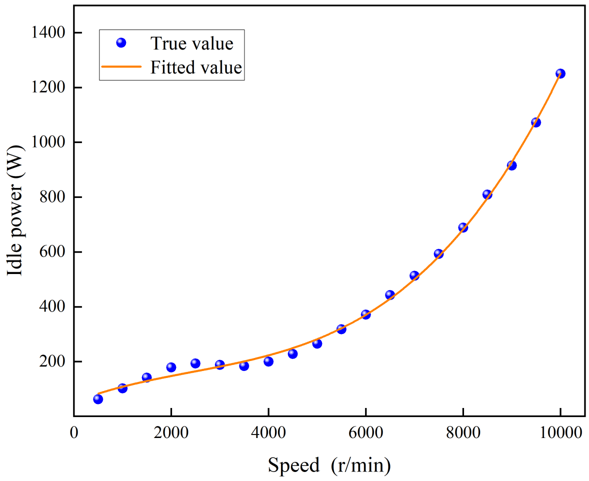
Table 2
Intrinsic energy consumption model and R^2 results of the VMC1165H spindle system in all stages

Parameter	Fitting function	R^2
E_{st}	$y = 405 + 0.66n - 4.12\times10^{-4}n^2 + 7.29\times10^{-8}n^3$	0.980
P_{u}	$y = 52.7 + 0.07n - 1.36\times10^{-5}n^2 + 1.92\times10^{-9}n^3$	0.998
E_{bk}	$y = -1300 + 1.91n - 5.48\times10^{-4}n^2 + 6.27\times10^{-8}n^3$	0.995

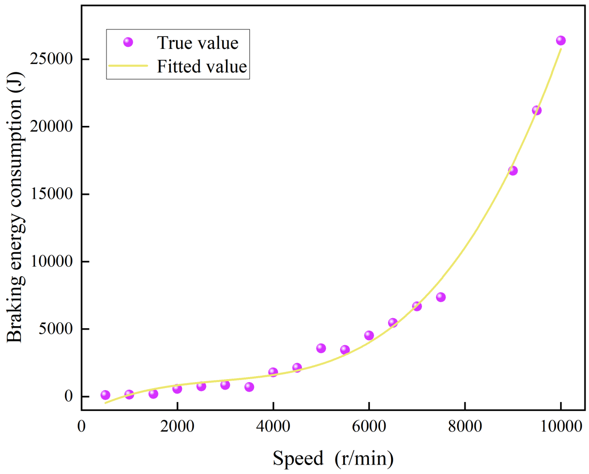
The R^2 value of the start-up energy consumption model is 0.980, and the fitting error is small in the low-speed range. The growth rate of start-up energy consumption accelerates in the high-speed range, but the fitting curve can still follow the actual data changes well. This phenomenon is because the spindle system needs to overcome greater rotational inertia at high speeds, and the peak starting current of the motor is higher, resulting in a non-linear increase in energy consumption.



(a) Start-up energy consumption stage



(b) Idle power stage



(c) Braking energy consumption stage

Fig. 6. Fitting diagram of the inherent energy consumption of VMC1165H in all stages

The R^2 value of the idle power model is 0.998, and the fitted curve completely overlaps with the actual data points. As the speed increases, the power curve shows a significant linear growth trend because the energy consumption generated by the spindle during stable idle operation is used to overcome steady-state losses such as bearing friction and air resistance, which are approximately linearly related to speed.

The R^2 value of the braking energy consumption model is 0.995. The variation law of braking energy consumption with rotational speed is similar to that of start-up energy consumption, but the value is slightly lower than that of start-up energy consumption at the same rotational speed. This is because during the braking process, some energy is fed back to the braking system, reducing the actual energy loss.

In summary, the R^2 values of all three models reached 0.98, indicating that this method has acceptable prediction accuracy for different spindle speeds.

4.3. Research on universality

In this study, the vertical machining center VMC855H is used to verify the inherent energy consumption modeling of the above spindle system at all stages. The experimental platform is set up as shown in Fig. 7, using the same instruments and test methods as VMC1165H, and the experimental results are shown in Table 3.

Fig. 7. VMC855H power measurement test platform

The data of VMC855H vertical machining center are sorted out, and the start-up energy consumption, idle power, and braking energy consumption are fitted in the above way. The obtained function fitting diagram is shown in Fig. 8, and the fitting function model and its R^2 results are shown in Table 4. From the fitting results, the R^2 values of the three models of vmc855H also reached 0.98, which was fundamentally similar to VMC1165H, which shows that the method has certain universality for the prediction of the whole stage inherent energy consumption of the spindle system of different machine tools.

The full-stage inherent energy consumption model and evaluation index system proposed in this paper are primarily applicable to CNC vertical machining centers utilizing electric spindles/mechanical transmission spindles and can be extended to CNC machine tools with the same spindle working stages, such as horizontal machining centers and gantry machining centers. This model is suitable for energy consumption modeling and evaluation of spindle systems with a speed range of 0–10 000 r/min. For spindle systems with different speed ranges,

Table 3
Inherent energy consumption of the VMC855H spindle system in all stages

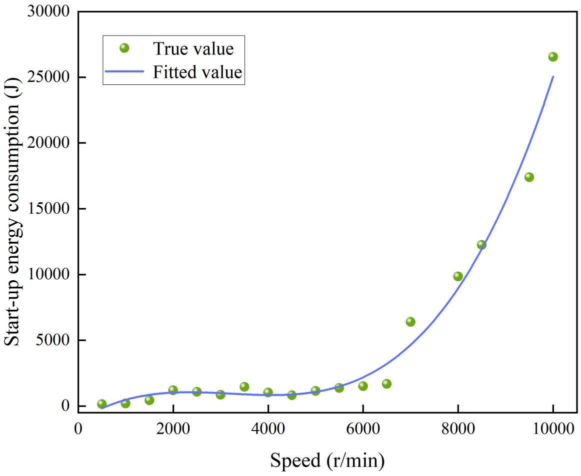
Speed (r/min)	Start-up energy consumption (J)	Braking energy consumption (J)	Idle power (W)
500	147.4	141.5	49.7
1000	197.0	142.1	79.4
1500	432.1	285.9	106.2
2000	1190.8	316.1	127.7
2500	1078.9	357.1	139.2
3000	843.5	599.7	144.0
3500	1462.1	512.3	155.5
4000	1020.6	516.2	174.6
4500	817.8	1200.7	197.4
5000	1137.3	1511.4	214.8
5500	1372.0	1759.3	251.1
6000	1502.7	2558.7	288.4
6500	1679.1	3233.6	327.9
7000	6394.2	2768.6	380.5
7500	12482.5	3021.5	436.4
8000	9838.8	3768.6	500.4
8500	12251.3	4773.4	587.5
9000	12201.0	4842.2	672.8
9500	17397.2	5956.7	914.0
10000	26548.5	8340.0	1036.7

Table 4
Intrinsic energy consumption model and R2 results of VMC855H spindle system in all stages

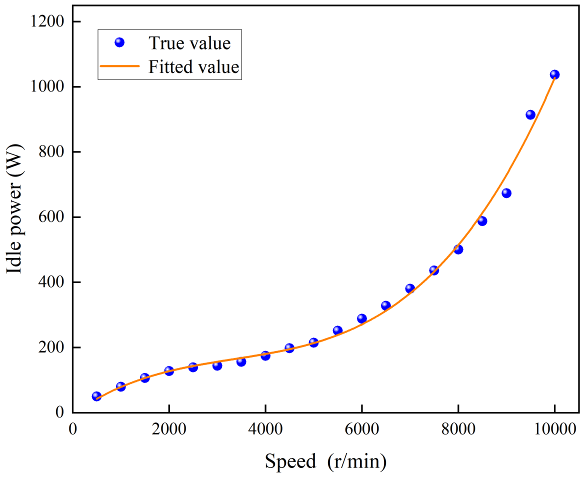
Parameter	Fitting function	R^2
E_{st}	$y=-1160+2.33n-7.84\times10^{-4}n^2+8.12\times10^{-8}n^3$	0.982
P_u	$y=-3.75+0.10n-2.42\times10^{-5}n^2+2.41\times10^{-9}n^3$	0.995
E_{bk}	$y=-228+0.47n-1.06\times10^{-5}n^2+1.38\times10^{-9}n^3$	0.983

the parameters of the fitting function can be modified to adapt them.

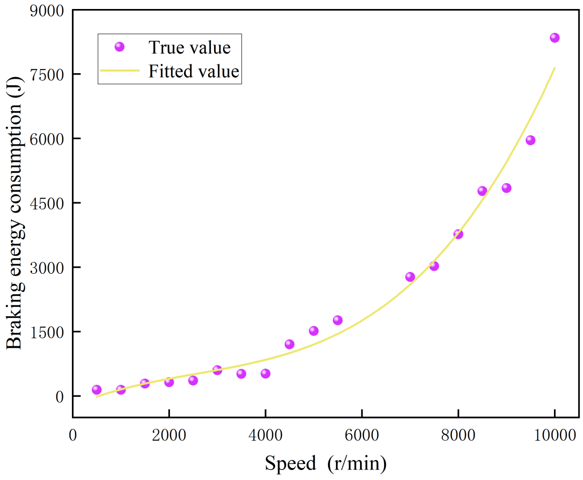
The energy consumption of two types of machine tools is evaluated and calculated according to formulas (2)–(7), and the results are shown in Table 5. It can be seen that the energy consumption expectation of VMC1165H spindle system start-up, idle power expectation and braking energy consumption expectation are higher than VMC855H, which indicates that VMC855H has a more prominent energy consumption advantage in the processing task requiring frequent spindle start-up and shutdown, and can reduce energy loss in the process. The lower the value, the lower the energy consumption per unit mass of the spindle, and the higher the energy efficiency level. Although part of energy consumption indicators achieved by VMC1165H are poor, its mass energy ratio is better, indicating that its spindle quality and energy consumption match better. Thus, it may have more advantages in spindle material selection and structure optimization. However, VMC855H has room for



(a) Start-up energy consumption stage



(b) Idle power stage



(c) Braking energy consumption stage

Fig. 8. Fitting diagram of inherent energy consumption of VMC855H in all stages

further lightweight design. By reducing the mass of the spindle, the mass energy ratio can be improved, and the overall energy efficiency can be optimized.

Table 5
Evaluation results of the inherent energy consumption of the spindle system at all stages

Machine model	VMC1165H	VMC855H
Start-up energy consumption expectation (J)	4324.9	3850.2
Idle power expectation (W)	1321.6	1105.8
Braking energy consumption expectation (J)	3462.5	2980.7
Inherent mass-to-energy ratio	0.0303	0.0325

5. CONCLUSIONS

In this paper, the inherent energy consumption model of the whole stage (standby, start-up, idle, braking) of the spindle system is constructed, and the evaluation system, including power expectation, energy consumption expectation, and mass energy ratio, is proposed. The effectiveness of the method is verified by a case. The main conclusions are as follows:

1. The energy consumption in the non-cutting stage of the spindle system cannot be ignored. The instantaneous peak power in the start-up and braking stages can reach more than 1.5 times the rated power, and the energy consumption in the idle stage accounts for more than 50% of the total non-cutting energy consumption.
2. The mathematical fitting function is developed to calculate the inherent energy consumption of the spindle system at any speed of the machine. The proposed fitting function R2 is higher than 0.98, indicating that the model has sufficient prediction accuracy at all speeds of the spindle system.
3. The inherent mass energy ratio index of the spindle system can effectively quantify the energy consumption mass matching degree and idle efficiency of the spindle and provide a quantitative basis for the lightweight design and process optimization of the machine tool.

The future research can be extended to the cutting stage, and the "all working conditions – all stages" can be constructed. At the same time, combined with machine learning, the probability distribution of rotational speed can be optimized to further improve the practicability of the evaluation index.

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REFERENCES

[1] T. Gutowski, J. Dahmus and A. Thiriez. "Electrical energy requirements for manufacturing processes," in *Proc. 13th. CIRP Int. Conf. LCE*, 2006, pp. 623–638.

[2] S. Kara and W. Li. "Unit process energy consumption models for material removal processes," *CIRP Ann: Manuf. Techn.*, vol. 60, pp. 37–40, 2011, doi: 10.1016/j.cirp.2011.03.018.

[3] S.A. Bagaber and A.R. Yusoff. "Energy and cost integration for multi-objective optimisation in a sustainable turning process," *Measurement*, vol. 136, pp. 795–810, 2019, doi: 10.1016/j.measurement.2018.12.096.

[4] S. Pawanr, G.K. Garg, and S. Routroy, "Prediction of energy consumption of machine tools using multi-gene genetic programming," *Mater. Today Proc.*, vol. 58, pp. 135–139, 2022, doi: 10.1016/j.matpr.2022.01.156.

[5] S. Pawanr, G.K. Garg, and S. Routroy, "A novel approach to model the energy consumption of machine tools for machining cylindrical parts," *J. Manuf. Process.*, vol. 84, pp. 28–42, 2022, doi: 10.1016/j.jmapro.2022.09.040.

[6] D. Pantazis, P. Goodall, and P.S. Grace. "Predicting electrical power consumption of end milling using a virtual machining energy toolkit (V_MET)," *Comput. Ind.*, vol. 150, p. 103943, 2023, doi: 10.1016/j.compind.2023.103943.

[7] S. Velchev *et al.*, "Empirical models for specific energy consumption and optimization of cutting parameters for minimizing energy consumption during turning," *J. Clean. Prod.*, vol. 80, pp. 139149, 2014, doi: 10.1016/j.jclepro.2014.05.099.

[8] N. Diaz-Elsayed, D. Dornfeld, and A. Horvath. "A comparative analysis of the environmental impacts of machine tool manufacturing facilities," *J. Clean. Prod.*, vol. 95, pp. 223–231, 2015, doi: 10.1016/j.jclepro.2015.02.047.

[9] Z. Liu, M.P. Sealy, and W. Li, "Energy consumption characteristics in finish hard milling," *J. Manuf. Process.*, vol. 35, pp. 500–507, 2018, doi: 10.1016/j.jmapro.2018.08.036.

[10] J. Tou, F. Liu and H. Zhang. "Connotation of inherent energy efficiency of machine tools and their evaluation method," *Chin. J. Mech. Eng.*, vol. 54, no. 7, pp. 167–175, 2018, doi: 10.3901/JME.2018.07.167. (in Chinese)

[11] J. Huang, F. Liu and J. Xie. "A method for determining the energy consumption of machine tools in the spindle start-up process before machining" *Proc. IMechE Part B: J. Engineering Manufacture*, vol. 230, no. 9, pp. 1639–1649, 2016, doi: 10.1177/0954405415600679.

[12] J. Lv, R. Tang and W. Tang. "An investigation into reducing the spindle acceleration energy consumption of machine tools," *J. Clean. Prod.*, vol. 143, pp. 794–803, 2017, doi: 10.1016/j.jclepro.2016.12.045.

[13] S. Pawanr, G.K. Garg and S. Routroy. "Development of a transient energy prediction model for machine tools," *Procedia Cirp*, vol. 98, pp. 678–683, 2021, doi: 10.1016/j.procir.2021.01.174.

[14] S. Jia, R. Tang, J. Lv, Q. Yuan, and T. Peng, "Energy consumption modeling of machining transient states based on finite state machine," *Int. J. Adv. Manuf. Technol.*, vol. 88, no. 5, pp. 2305–2320, 2017, doi: 10.1007/s00170-016-8952-2.

[15] S. Jia, Q. Yuan, D. Ren, and J. Lv, "Energy demand modeling methodology of key state transitions of turning processes, *Energies*, vol. 10, no. 4, p. 462, 2017, doi: 10.3390/en10040462.

[16] L. Ma, C. Song, C. Dou, and T. Yang, "Evaluation Method of Machine Tool Energy Efficiency Based on PSO-SVM Algorithm," *Control Eng. Chin.*, vol. 28, no. 2, pp. 200–206, 2021, doi: 10.14107/j.cnki.kzgc. 20200062. (in Chinese)

[17] X. Wang, Q. Zhu, P. Liu, and F. Yu, "Multi-scene Comprehensive Evaluation of Energy Efficiency Testing Methods for Machine Tools," *Chin. J. Mech. Eng.*, vol. 59, no. 7, pp. 265–275, 2023, doi: 10.3901/JME.2023.07.265. (in Chinese)

[18] J. Cui, C. Li, H. Cao, X. Chen, J. Wang, and T. Dai, "SOM-Kmeans Based Machine Tools Energy Efficiency Grade Evaluation," *Chin. J. Mech. Eng.*, vol. 59, no. 7, pp. 295–306, 2023, doi: 10.3901/JME.2023.07.295. (in Chinese)

[19] F. Ma, H. Zhang, Q. Gong, and K.K.B. Hon, "A novel energy efficiency grade evaluation approach for machining systems based on inherent energy efficiency," *Int. J. Prod. Res.*, vol. 59, no. 19, pp. 6022–603, 2021, doi: 10.1080/00207543.2020.1799104.

[20] K. Lai, H. Cao, H. Li, B. Li, and D. Huang, "Coupling evaluation for material removal and thermal control on precision milling machine tools," *Front. Mech. Eng.*, vol. 17, no. 1, p. 12, 2022, doi: 10.1007/s11465-021-0668-9.

[21] J. Zhang *et al.*, "Thermal energy efficiency evaluation of cutting space for dry cutting machine tools: An exergy time-varying graphical method," *Energy*, vol. 332, p. 137220, 2025, doi: 10.1016/j.energy.2025.137220.

[22] X. Liu, H. Yang, L. Xing, Y. Wang, L. Qiu, and S. Zhang, "Energy Efficiency Evaluation of Five-axis Machine Tools with Different Configurations based on Workspace Stiffness and Machining Energy Consumption," in *IEEE 20th. Int. Conf. Autom. Sci. Eng.*, 2024, pp. 3642–3647. doi: 10.1109/CASE59546.2024.10711347.

[23] C. Naumann *et al.*, "Evaluation of thermal error compensation strategies regarding their influence on accuracy and energy efficiency of machine tools," in *GCSM 18th. Manuf. Driving Circ. Econ.*, 2022, pp. 157–165. doi: 10.1007/978-3-031-28839-5_18.

[24] A. Can, H. Schulz, A. El-Rahhal, G. Thiele, and J. Krüger, "A practical approach to realize a closed loop energy demand optimization of milling machine tools in series production," in *GCSM 18th. Manuf. Driving Circ. Econ.*, 2022, pp. 499–507, doi: 10.1007/978-3-031-28839-5_56.

[25] X. Hu, Y. Tian, J. Wang, S. Wang, J. Han, and Y. Liu, "Energy index for evaluating machine tool energy performance: classification, model and application," *J. Clean. Prod.*, vol. 447, p. 141356, 2024, doi: 10.1016/j.jclepro.2024.141356.