



# An investigation into reducing the spindle acceleration energy consumption of machine tools



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## ABSTRACT

Machine tools are widely used in the manufacturing industry, and consume large amount of energy. Spindle acceleration appears frequently while machine tools are working. It produces power peak which is highly energy intensive. As a result, a considerable amount of energy is consumed by this acceleration during the use phase of machine tools. However, there is still a lack of understanding of the energy consumption of spindle acceleration. Therefore, this research aims to model the spindle acceleration energy consumption of computer numerical control (CNC) lathes, and to investigate potential approaches to reduce this part of consumption. The proposed model is based on the principle of spindle motor control and includes the calculation of moment of inertia for spindle drive system. Experiments are carried out based on a CNC lathe to validate the proposed model. The approaches for reducing the spindle acceleration energy consumption were developed. On the machine level, the approaches include avoiding unnecessary stopping and restarting of the spindle, shortening the acceleration time, light-weight design, proper use and maintenance of the spindle. On the system level, a machine tool selection criterion is developed for energy saving. Results show that the energy can be reduced by 10.6% to more than 50% using these approaches, most of which are practical and easy to implement.

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## 1. Introduction

Energy plays an indispensable role in industry sector. Approximately one third (31.8%) of the total world primary energy is consumed by industrial sector (EIA, 2016). The industrial sector is the largest source of greenhouse gas, and accounts for 29.2% of electricity-related CO<sub>2</sub> emissions (EPA, 2016). Thus sustainable manufacturing has drawn increasing attention from both academia and industry (Zhang et al., 2016). Machine tools are highly energy consumable and widely used in industrial sector; for instance, there are over 7 million machine tools in China (Liu et al., 2015a) involved in machining. As a result, a considerable amount of energy is consumed during the use phase of machine tools. Therefore,

improving the energy efficiency of machine tool can yield significant reduction in the environmental impact.

The energy consumption of machine tools can be evaluated by taking into account both steady state and transient state regimes (Avram and Xirouchakis, 2011). During the steady state, the machine tool operates at constant parameters, which leads to constant power consumption. Energy consumption modeling of machine tool operations in the steady state have been studied by many researchers, such as spindle rotation, feed and cutting (Balogun and Mativenga, 2013; Lv et al., 2014). The transient state deals with the start or the status changes of the machine tool subsystem, such as machine tool startup, coolant on and spindle acceleration, which always leads to power spike. The transient state appears frequently and produces power peak which is highly energy intensive during the machining process. As a result, a considerable amount of energy is consumed during the transient state of machine tool. Ignorance of this part of energy may lead to an underestimation of the total

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energy consumption during machining processes. For instance, the estimated value of the total energy consumption of a milling process is about 9.3% less than the actual one (He et al., 2012). Preliminary experiments on milling and turning processes indicated that spindle acceleration accounts for the largest proportion of the energy consumed in transient state (Avram, 2010; Jia, 2014). For instance, the energy consumption of spindle acceleration (ESA) is about 32.91 kJ, which accounts for 62.9% of energy consumed (52.28 kJ) by the transient state of machine tool during high-speed milling of a 2.5D part (Avram, 2010). In order to reduce the ESA, there is a need to develop accurate energy consumption model of spindle acceleration.

Spindle acceleration is the process of spindle starting up from standby state or accelerating to a higher rotational speed without cutting load. The energy consumption model is very complicated, which is determined by the inverter control of spindle motor and the inertia of mechanical transmission chains. Therefore, the ESA is mainly acquired experimentally in the previous study (Avram and Xirouchakis, 2011; Mori et al., 2011). However, the acquisition of spindle acceleration energy through experiment is cost and labor intensive. In addition, the lack of models makes it impossible to evaluate the energy of spindle acceleration in the machine tool design phase, thus difficult to be used for energy-efficient design of machine tool.

The aim of this study is to understand the spindle acceleration energy consumption of computer numerical control (CNC) machine tools, and to explore the methods to save the spindle acceleration energy based on the proposed model. The structure of this paper is as follows. In Section 2, a review of current study on the energy consumption modeling of spindle acceleration and energy saving approaches of machine tool is carried out. In Section 3, model of the ESA is developed, and the calculation process of the related coefficients from parameters of the spindle mechanical transmission and motor control is given. In Section 4, effectiveness of the proposed model is demonstrated by comparing the calculation and measurement results of the ESA. In Section 5, approaches of reducing the ESA are investigated based on the proposed model. Finally in Section 6 the conclusions are drawn and future work is discussed.

## 2. Background and motivation

This paper is mainly related to two research areas: modeling spindle acceleration energy consumption and approaches for improving the energy efficiency of machine tools. The related state-of-the-art researches are summarized below.

### 2.1. Energy consumption modeling of spindle acceleration

The peak power of machine tools in transient state has been studied by many researchers. One of the earliest studies presented by Li et al. (2011) measured the peak power of six different machine tools. The power ranged from 2.4 kW for the MS Dura Vertical 5100 up to 9 kW for the DMU 60P. Similar tests were conducted on nine different machine tools, and the peak power varied from 3.3 kW for the NVD1500 to 55.6 kW for the NH8000 (Behrendt et al., 2012). Power peak due to spindle acceleration can be found in many literature, such as power profile of milling process done on a Hitachi Seiki VG45 machine tool (Aramcharoen and Mativenga, 2014), power data of the HAAS VF5.50 for milling a pallet (Wang et al., 2015) and power profile of spindle activation on a Hurco VM2 CNC machine tool (O'Driscoll et al., 2015). However, the ESA was not further modeled in the above literature.

In recent years, researchers have focused on studying the energy consumption of machine tools in steady state, such as fixed energy

(Li et al., 2011), coolant spraying energy (Kara and Li, 2011) and cutting energy (Liu et al., 2015b), while ESA has received limited attention. For instance, a comprehensive literature review on the energy consumption model and energy efficiency of machine tools was presented by Zhou et al. without considering the ESA (Zhou et al., 2016). For the modeling of ESA, Avram and Xirouchakis (2011) modeled the spindle acceleration power by multiplying the angular velocity and acceleration torque. The acceleration torque includes torque required to accelerate the total spindle moment of inertia and the torque required to overcome the mechanical losses of the spindle system. This model is hard to apply in practice, since there is still a lack of method to calculate the acceleration torque. Other models of the ESA are empirical and can be divided into two types. The first type of models is to express the spindle start-up energy of machine tool as a quadratic function of the spindle speed, such as models presented by Shi et al. (2009) and Huang et al. (2016). The second type of model obtains the ESA by integrating the instantaneous power over time, such as the model proposed by Lv (2014). The accuracy of the above two types of models were evaluated by experiments conducted on a CK6153i CNC lathe (Zhong et al., 2016). Results showed that the first type of model is able to predict the ESA with an accuracy of over 87%, and the second type of model supports an accuracy of over 85%. Thus the first type of model is much easier and more reliable for calculating the ESA (Zhong et al., 2016). However, these two types of empirical models need cost and laborious experiments to collect the spindle acceleration power data which are used to obtain the model coefficients by regression analysis. In addition, the first type of model is incapable of being applied to estimate the energy consumed of machine tool when the spindle is accelerating from a low speed (not zero) to a higher speed.

### 2.2. Approaches for improving the energy efficiency of machine tools

Different strategies have been considered to increase the energy efficiency of machine tools. While Duflo et al. (2012) provide an overview of increasing process efficiency by optimizing the machine tool design, Yoon et al. (2015) presented a very comprehensive review on energy saving strategies and technologies of machine tools. It is to be noted that machine tools are expected to become more compact and lightweight in order to increase the energy efficiency. Two types of approaches are often used to improve the energy efficiency of machine tools: lightweight design approaches and control approaches. The lightweight design approaches can be divided into two types: structural lightweight design using topological optimization, and material lightweight design by using new materials such as titanium materials, metal foam or reinforced carbon-fiber composites (Kroll et al., 2011). For instance, the ram of a bridge-type machining center was redesigned using modular boxes built with carbon-fiber trusses (Bustillo et al., 2015). The new design leads to a 60% reduction in mass and a 35% reduction in energy consumed by the Y-axis motor during no-load motions. The control approaches deal with energy saving control for feed drive systems. Okwudire and Rodgers (2013) presented the design and control of a novel hybrid feed drive which has the potential to achieve accuracies and speeds while significantly reducing the electricity consumption. Mohammad et al. (2014) reduced the energy consumed by about 12.9% of the ball-screw feed-drive systems by a novel sliding-mode controller with a nonlinear sliding surface. Uchiyama et al. (2015) proposed a synchronous and contouring control method to save the energy in five-axis machine tools, the proposed method reduces energy consumption of the feed drive by 13.2% on average compared to the conventional design. However, to the best of our knowledge, there

are no prior papers studies on reducing the spindle acceleration energy consumption of machine tools.

Based on the discussion above, the motivation of this research is employing the theory of spindle mechanical transmission and motor control to model the spindle acceleration energy consumption of CNC machine tools. The lack of a fundamental energy models of spindle acceleration and its related energy saving methods are significant gaps in the current research which needs to be addressed. Based on the energy models, the approaches to reduce the ESA, for instance, the lightweight design and control approaches can be developed.

For this research, the ESA only includes the energy consumed by the spindle motor. The idle power of machine tools is excluded, since it is a constant and does not vary with the spindle acceleration operations. The modeling method for the ESA will be presented below.

### 3. Modeling energy consumption of spindle acceleration

The most common spindle drive motors are induction motors which are controlled by inverter. Without loss of generality, the proposed model will be developed based on the induction motors. The power of spindle acceleration is significantly higher than that in the steady-state, because the torque required to accelerate the spindle system is substantially greater than the torque required to keep it running. Take a CK6153i CNC lathe for example, the power profile of spindle acceleration is shown in Fig. 1. The spindle acceleration starts at the moment when the power begins to increase. The spindle acceleration finishes when the power reaches to its highest value. The power of spindle acceleration consists of two parts. The first part is the direct power to maintain the spindle rotation, which equals to the spindle rotation power at the specified spindle rotational speed. The second and often most important part is the power to overcome the inertia of the mechanical transmission system of spindle drive and accelerate the spindle, which equals to the product of acceleration torque and the spindle motor angular speed. The power of spindle acceleration  $P_{SA}$  [W] is expressed as:

$$P_{SA} = P_{SR}(n) + T_{SA}\omega_M \quad (1)$$

where  $P_{SR}$  is the spindle rotation power [W],  $n$  is the spindle rotational speed [r/min],  $\omega_M$  is the angular speed of spindle motor [rad/s],  $T_{SA}$  is the equivalent acceleration torque of the spindle drive system referred to spindle motor shaft [N·m]. It can be expressed as:

$$T_{SA} = J_{sp}\alpha_M \quad (2)$$

where  $J_{sp}$  is the equivalent moment of inertia for spindle drive system referred to spindle motor shaft [ $\text{kg}\cdot\text{m}^2$ ],  $\alpha_M$  is the angular acceleration of spindle motor [rad/s<sup>2</sup>].

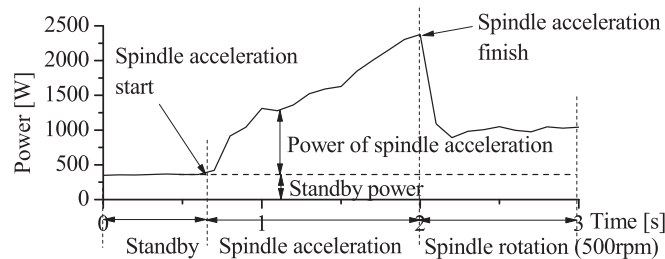


Fig. 1. Power profile of spindle acceleration for CK6153i CNC lathe.

Assuming the spindle rotational speed is increased from  $n_1$  to  $n_2$ , the spindle acceleration time is:

$$t_{SA} = \frac{2\pi(n_2 - n_1)}{60\alpha} \quad (3)$$

where  $t_{SA}$  is the time period of spindle acceleration process [s],  $n_1$  is the initial spindle speed before acceleration [r/min],  $n_2$  is the final spindle speed after acceleration [r/min],  $\alpha$  is the angular acceleration of spindle [rad/s<sup>2</sup>]. Then the energy consumption  $E_{SA}$  of spindle acceleration is:

$$E_{SA} = \int_0^{t_{SA}} P_{SA} dt \quad (4)$$

Expressions (1)–(4) are with many coefficients which can be divided into two types: the variable parameters and fixed parameters. The former include spindle rotational speed  $n$  and the angular speed of spindle motor  $\omega_M$ , which is controlled by the spindle inverter; the later include moment of inertia  $J_{sp}$ , angular acceleration of spindle motor  $\alpha_M$  and angular acceleration of spindle  $\alpha$ , which are functions of mechanical design and motor control parameters of the spindle system.

The rotational speed of spindle motor  $n_M$  [r/min] of CNC machine tool is controlled by adjusting the inverter output frequency, which is given by (Fitzgerald et al., 2003):

$$n_M = \frac{60f_1}{p}(1 - s) \quad (5)$$

where  $f_1$  is the electrical frequency controlled by spindle inverter [Hz],  $p$  is the number of pole pairs of the motor,  $s$  is the motor slip. The value of slip  $s$  is usually between 0.01 and 0.05, depending on the load of the spindle motor. The spindle motor load is small, since the spindle is accelerated with no cutting load. As a result, the slip  $s$  is near zero and  $1 - s \approx 1$ . Then Eq. (5) is simplified as:

$$n_M \approx \frac{60f_1}{p} \quad (6)$$

The spindle speed  $n$  is determined by the motor speed multiplied by the drive ratio:

$$n = u_i n_M \quad (7)$$

where  $u_i$  is the drive ratio of  $i$ -th drive chain to the spindle motor shaft.

Substituting Eq. (6) into Eq. (7), we get:

$$n = \frac{60u_i f_1}{p} \quad (8)$$

During the process of spindle acceleration, the output frequency of spindle inverter increases linearly. The rise rate of the inverter output frequency is determined by the acceleration time that is the time required by the output frequency to be increased from 0 Hz to the maximum frequency, is given by:

$$k_A = f_M / t_A \quad (9)$$

where  $k_A$  is the rise rate of the output frequency [Hz/s],  $f_M$  is the maximum out frequency of the inverter [Hz],  $t_A$  is the acceleration time preset in spindle inverter [s].

During the process of spindle acceleration, the inverter output frequency  $f_1$  is calculated as:

$$f_1 = f_{11} + k_A t \quad (10)$$

where  $f_{11}$  is the inverter output frequency when the spindle speeds are  $n_1$  [Hz],  $t$  is the time of spindle acceleration [s]. Now, the relation between the spindle rotational speed and the spindle system design parameters can be found from Eqs. (8) (9) and (10) as:

$$n = n_1 + \frac{60 u_i f_M t}{p t_A} \quad (11)$$

By applying Eq. (11), Eq. (7) becomes:

$$n_M = \frac{n}{u_i} = \frac{n_1}{u_i} + \frac{60 f_M t}{p t_A} \quad (12)$$

The angular speed of spindle motor  $\omega_M$  is calculated as:

$$\omega_M = \frac{2\pi}{60} n_M = \frac{2\pi n_1}{60 u_i} + \frac{2\pi f_M t}{p t_A} \quad (13)$$

By applying Eq. (13), the angular acceleration of spindle motor can be computed as:

$$\alpha_M = \frac{d\omega_M}{dt} = \frac{2\pi f_M}{p t_A} \quad (14)$$

By applying Eq. (11), the angular acceleration of spindle can be computed as:

$$\alpha = \frac{d\omega}{dt} = \frac{2\pi}{60} \frac{dn}{dt} = \frac{2\pi u_i f_M}{p t_A} \quad (15)$$

The moment of inertia  $J_{sp}$  can be expressed as (Liu et al., 1995):

$$J_{sp} = J_e + J_m \quad (16)$$

where  $J_e$  is the rotor inertia of spindle motor [ $\text{kg} \cdot \text{m}^2$ ],  $J_m$  is the equivalent moment of inertia for mechanical transmission system of spindle drive referred to spindle motor shaft [ $\text{kg} \cdot \text{m}^2$ ], which is given by (Liu et al., 1995):

$$J_m = j_2^2 J_2 + \sum_{i=3}^m \prod_{k=2}^{i-1} (1 + b_k) j_i^2 J_i \quad (17)$$

where  $j_i$  is the transmission ratio of  $i$ -th transmission link referred to spindle motor shaft,  $b_k$  is the load dependent power loss factor of  $k$ -th transmission link,  $J_i$  is the total moment of inertia of the components in  $i$ -th transmission link,  $m$  is the number of transmission links.

Actually, the factor  $b_k$  is small, for instance, the load dependent power loss factor of a transmission links which includes two bearings and a gear is only 0.012 (Liu et al., 1995), thus  $b_k \ll 1$ . Noting that the mechanical transmission chain of CNC machine

tools is short, thus  $\prod_{k=2}^{i-1} (1 + b_k) \approx 1$ , Eq. (17) becomes:

$$J_m = \sum_{i=2}^m j_i^2 J_i \quad (18)$$

The components of spindle system machine tool mainly include pulleys, shafts, gears, spindle and chuck. The shafts and chuck are cylinders made by solid steel materials. The moment of inertia  $J_i$  is calculated as (King, 2012):

$$J_i = \frac{MD^2}{8} = \frac{\pi}{32} \rho L D^4 \quad (19)$$

where  $M$  is the mass of a cylinder part [kg],  $D$  is the diameter of the cylinder part [m],  $L$  is the length or the thickness of the cylinder part [m],  $\rho$  is the material density of the spindle component [ $\text{kg}/\text{m}^3$ ].

The spindle, pulley and gear are hollow cylinder parts. Their moment of inertia is calculated as:

$$J_i = \frac{\pi}{32} \rho L (D_2^4 - D_1^4) \quad (20)$$

where  $D_2$  is the outer diameter [m],  $D_1$  is the inside diameter [m]. For shafts, spindle and gears made from steel,  $\rho = 7.85 \times 10^3 \text{ kg}/\text{m}^3$ . For pulley and chuck made from cast iron,  $\rho = 7.3 \times 10^3 \text{ kg}/\text{m}^3$ . In next section, the effectiveness of the proposed power, time and energy consumption models are validated.

Spindle acceleration and spindle deceleration are two opposite processes. For CNC machine tools, the spindle deceleration is also controlled by spindle inverter, the frequency of which is decreased to decelerate the spindle. The kinetic energy of the spindle system is converted back into electrical energy, and this part of energy is absorbed by the braking resistor or returned to the power grid. As a result, zero or negative values of energy consumption of spindle system could be observed during spindle deceleration.

#### 4. Model validation

Experiments of spindle acceleration were conducted on a CK6153i CNC lathe made by Jinan First Machine Tool Group Co., Ltd. The spindle is driven by a three-phase squirrel-cage asynchronous motor made by Shanghai Xianma Motor Co., Ltd. Then the power, time and energy of spindle acceleration were predicted using the proposed models and compared with those obtained from observation.

For a given machine tool, the energy of spindle acceleration is decided by values of initial and final spindle speeds. Hence, these two parameters were selected as process variables. The selected CK6153i CNC lathe has four transmission chains: AH, BH, AL and BL, as shown in Fig. 2. For each chain, two levels of initial and final spindle speeds were selected according to the spindle speed ranges, as presented in Table 1. Four experiments were conducted for each transmission using the combination of the initial and final spindle speeds in Table 1.

The power of machine tool was measured using the experimental setup including voltage transducers, current transducers, data acquisition card, chassis and NI Labview software. More information about the experimental setup details are available in (Lv et al., 2016a). The signals were sampled at a frequency of 5 kHz, and the power values were recorded every 0.1s. The power used for spindle acceleration is obtained by subtracting the idle power before spindle acceleration from the total power when the spindle is accelerating, as shown in Fig. 1. The experimental data can be found from (Lv et al., 2016b).

According to the models proposed in section 3, the power, time and energy of spindle acceleration models are determined (see Appendix A). Using the obtained models, the power, time and energy of spindle acceleration were simulated in MATLAB software with different combinations of initial and final spindle speeds (see Table 1). The comparison between the predicted and measured spindle acceleration power is shown in Fig. 3. It has been observed that the simulated values of the power by the proposed models shows a good agreement with the experimental data obtained with

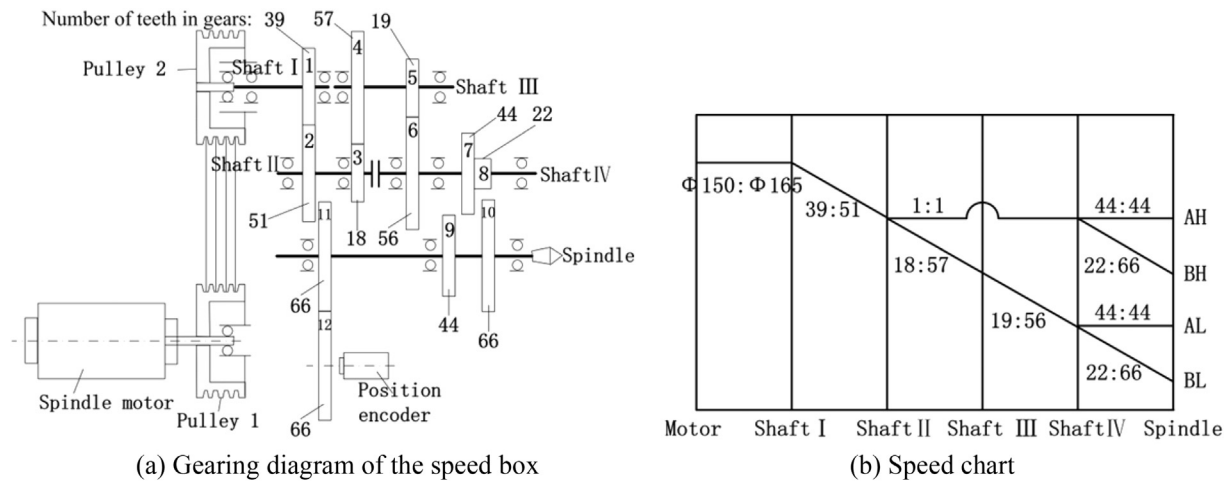


Fig. 2. Gearing diagram of the speed box and speed chart of CK6153i.

Table 1

Parameters and their levels of four different transmission chains in spindle acceleration experiments.

Transmission chain	AH		AL		BH		BL	
Parameters	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2
Initial speed [m/min]	0	500	0	100	0	50	0	15
Final speed [m/min]	1000	1500	300	500	100	150	30	45

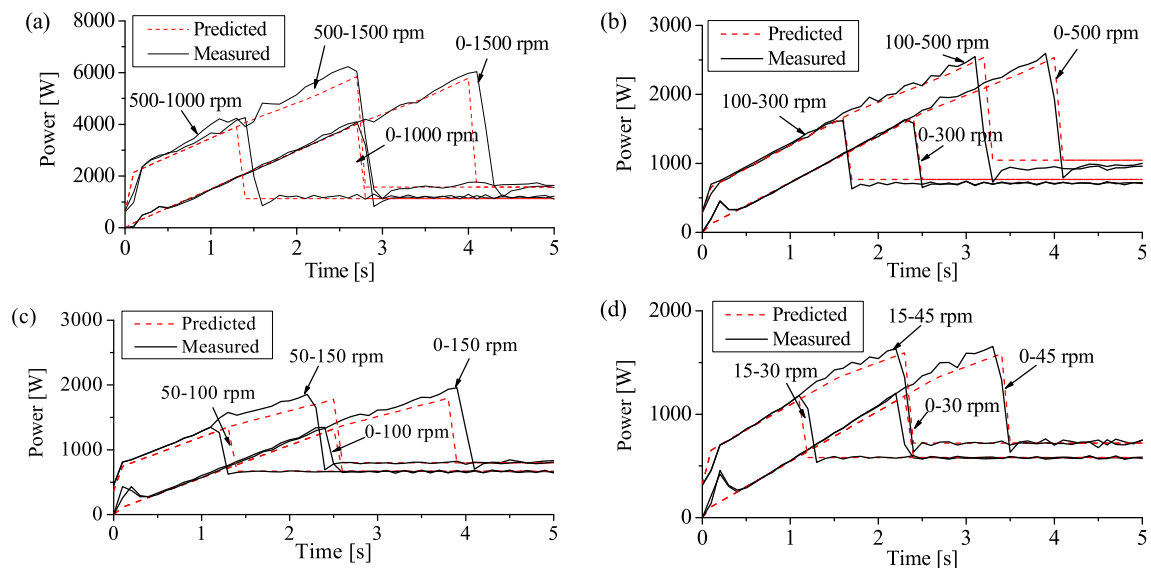


Fig. 3. Comparison between the predicted and measured spindle acceleration power of CK6153i: (a) AH transmission chain; (b) BH transmission chain; (c) AL transmission chain; (d) BL transmission chain.

different transmission chains. Apart from this, the predicted time and energy of spindle acceleration are close to the actual values measured experimentally, as shown in Table 2. The maximum errors between the predicted and measured results for the time and energy are 10.50% and 12.07%, respectively. The average errors are 4.60% and 5.82% for time and energy. Thus the proposed models can achieve a high prediction accuracy of power, time and energy of spindle acceleration. The predicted time and energy is less than the measured ones. This could be explained by the power of spindle acceleration needing 0.2–0.3 s to return to the normal value from the peak value. The model does not include this part of time and

energy, leading to less time and energy than the actual ones.

In the previous study, energy models of spindle acceleration have been proposed by Shi et al. (2009) and Lv (2014). Unknown coefficients in the models are obtained through regression analysis based on measured energy data of spindle acceleration. The accuracy of two models were validated by experiments of spindle acceleration with two groups of initial and final spindle speeds on the CK6153i CNC lathe with AH transmission chain (Zhong et al., 2016). For consistency, we choose the same initial and final spindle speeds as those in the spindle acceleration tests conducted by Zhong et al. (2016), to calculate the energy consumption using the proposed



**Table 2**

Comparison of predicted and measured time and energy of spindle acceleration for CK6153i.

Parameters			Time			Energy		
Transmission chain	Initial speed $n_1$ [r/min]	Final speed $n_2$ [r/min]	Predicted $t_{SA}^p$ [s]	Measured $t_{SA}^m$ [s]	Error $RE_t$ [%] <sup>a</sup>	Predicted $E_{SA}^p$ [J]	Measured $E_{SA}^m$ [J]	Error $RE_E$ [%] <sup>b</sup>
AH	0	1000	2.69	2.90	7.41	5638.50	6184.89	8.83
AH	0	1500	4.03	4.30	6.34	12,200.33	13,289.83	8.20
AH	500	1000	1.34	1.50	10.50	4047.10	4602.77	12.07
AH	500	1500	2.69	2.90	7.41	10,817.00	12,085.36	10.49
BH	0	300	2.42	2.50	3.33	2137.30	2248.33	4.94
BH	0	500	4.03	4.10	1.76	5529.10	5709.04	3.15
BH	100	300	1.61	1.70	5.22	1858.10	1914.90	2.97
BH	100	500	3.22	3.30	2.35	5254.30	5355.34	1.89
AL	0	100	2.51	2.50	0.25	1795.00	1907.91	5.92
AL	0	150	3.76	3.90	3.60	3852.30	4161.93	7.44
AL	50	100	1.25	1.30	3.60	1360.70	1360.99	0.02
AL	50	150	2.51	2.40	4.43	3260.30	3230.92	0.91
BL	0	30	2.26	2.40	6.03	1473.60	1587.42	7.17
BL	0	45	3.38	3.50	3.34	3036.20	3269.75	7.14
BL	15	30	1.13	1.20	6.03	987.51	1092.87	9.64
BL	15	45	2.26	2.30	1.94	2680.10	2744.15	2.33

<sup>a</sup>  $RE_t = |t_{SA}^p - t_{SA}^m| / t_{SA}^m \times 100\%$ .<sup>b</sup>  $RE_E = |E_{SA}^p - E_{SA}^m| / E_{SA}^m \times 100\%$ .

model. Accuracy of the energy consumption models for spindle acceleration are compared using experimental data from (Zhong et al., 2016). As can be seen from Table 3, the model we proposed provides an average accuracy of 89.58% for spindle acceleration, while the average accuracy of model proposed by Shi et al. (2009) and Lv (2014) are 87.92% and 87.79%, respectively. Thus the accuracy of the proposed model is slightly higher than that of the existing models in literature.

The proposed model can improve the prediction accuracy of the ESA. This could be explained by noting that both power of spindle rotation and spindle acceleration are considered in the proposed model, which can reflect the essence of the spindle acceleration process. In contrast, for the existing experimental model, the ESA is assumed to be a single-variable quadratic function of final spindle speed. Then the ESA is obtained by second order polynomial regression analysis using the experimental data. However, the actual model may be very different from the assumed quadratic model, which could lead to large errors in the prediction of the ESA. Therefore, the proposed model in this paper could have higher accuracy and wider applicability.

In order to investigate the power characteristics of spindle deceleration, experiments were conducted on two machine tools. Fig. 4(a) shows the power profile during spindle deceleration of CK6153i. The power consumed by spindle system is near zero when the spindle is decelerated from 1500 to 500 rpm, which could be explained by the kinetic energy of the spindle system being dissipated by the braking resistor. In Fig. 4(b), the spindle motor of XHK-714F milling center completed the acceleration process in 0.6 s and the energy consumed was 5.92 kJ. While decelerating a negative power peak of 8.46 kW was recorded and an energy of 3.16 kJ was released back into the mains, which accounted for 53.4% of the energy consumed in acceleration.

## 5. Discussion on energy reduction of spindle acceleration

This section will discuss about the energy reduction of spindle acceleration, as shown in Fig. 5. The energy consumption of spindle acceleration (ESA) can be saved on both machine level and system level. Based on the proposed model, the effect of the associated factors on the ESA were explored, thereby developing corresponding energy saving approaches.

### 5.1. Machine level

On the machine level, the value of ESA is affected by production requirements, moment of inertia and wear and tear of the spindle system. Here, the AH transmission chain of CK6153i CNC lathe is selected to study the influence of the aforementioned factors on the ESA.

Production requirements associated with the ESA include process parameters and takt time. The process parameters determine the value of spindle speeds. The takt time is the time in which a product must be produced to satisfy customer demand. It can be reduced by shortening the time required for spindle acceleration, thereby increasing production efficiency.

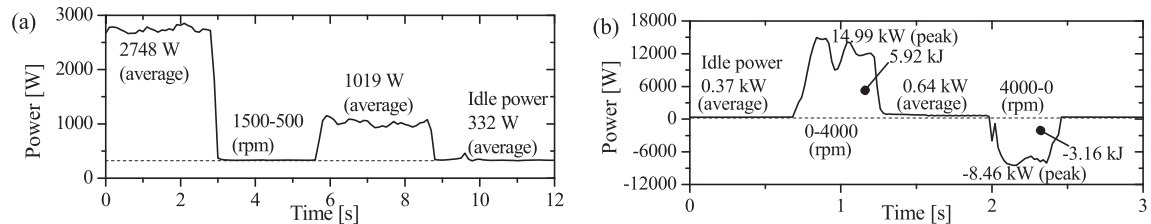
In order to explore the relationship between the ESA and spindle speeds, the ESA is predicted based on the experimentally verified model presented earlier, as shown in Fig. 6. It can be observed that more energy is needed if the spindle is started to attain a higher speed. As a result, high speed machining may consume more energy for spindle acceleration. However, this part of consumption could be counterbalanced by the energy saved during machining process due to significant time reductions. For the same final spindle speed, the ESA decreases with increasing initial spindle speed. This could be explained by the less kinetic

**Table 3**

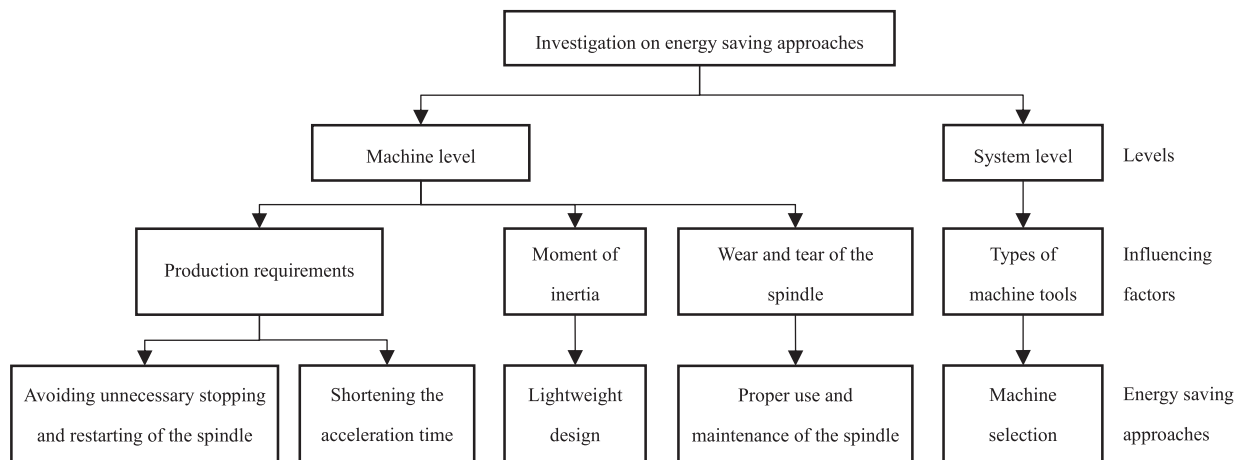
Accuracy comparison of energy consumption models for spindle acceleration for CK6153i.

Initial speed $n_1$ [r/min]	Final speed $n_2$ [r/min]	Measured Energy $E_{SA}^m$ [J]	Predicted Energy $E_{SA}^p$ [J]			Accuracy [%] <sup>a</sup>		
			Model by Shi et al. (2009)	Model by Lv (2014)	Proposed model	Model by Shi et al. (2009)	Model by Lv (2014)	Proposed model
0	750	3611.06	4074.45	4130.69	3237.29	87.92	85.61	89.65
500	1500	12,085.36	—	10,873.33	10,817.00	—	89.97	89.50

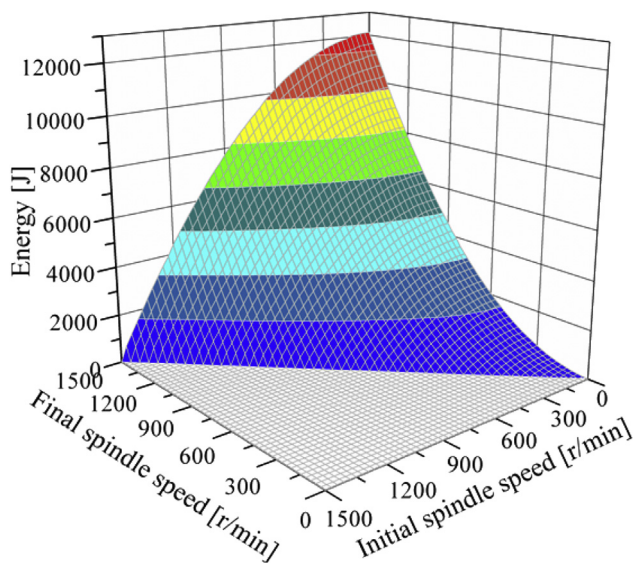
<sup>a</sup> Accuracy =  $(1 - |E_{SA}^p - E_{SA}^m| / E_{SA}^m) \times 100\%$ .



**Fig. 4.** Measured power profile of machine tools. (a) The spindle of CK6153i was decelerated from 1500 to 500 rpm, running at 500 rpm, and then stopped. (b) The spindle of XHK-714F milling center was accelerated from 0 to 4000 rpm followed by constant running and deceleration to 0 rpm.



**Fig. 5.** Architecture of the energy saving approaches for spindle acceleration.

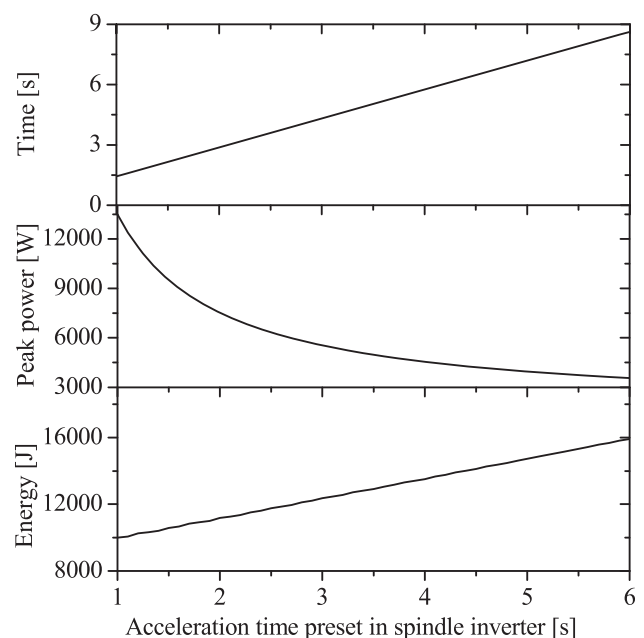


**Fig. 6.** Predicted energy consumption of spindle acceleration due to changes in initial and final spindle speeds.

energy being needed for spindle system to be accelerated from a higher initial speed. Therefore, if the spindle is already running at a relative low speed, it is better for the spindle to be accelerated directly to a higher speed instead of being stopped and restarted in order to save energy. For instance, after semi finishing, the spindle is recommended to be accelerated directly to a higher speed for finishing, which can save both time and energy.

For given spindle speeds, the time required for spindle

acceleration is determined by the acceleration time preset in the spindle inverter. The time, peak power and energy consumption calculated from the proposed models, when the spindle is accelerated from 0 to 1500 r/min, for various values of acceleration time, is shown in Fig. 7. As the acceleration time decreases, both time and



**Fig. 7.** Predicted time, peak power and energy consumption of spindle acceleration due to changes in acceleration time. The Spindle was accelerated from 0 to 1500 rpm.

energy consumption of spindle acceleration is decreased, which indicates that shortening takt time and reducing energy consumption can be realized simultaneously. However, the peak power increases dramatically, which may be beyond the power limit that the spindle motor can supply. This can be explained simply by noting that as the acceleration time decreases, the angular acceleration and acceleration torque increases, which requires more power to accelerate the spindle system. Thus the acceleration time should be set as short as possible to avoid wasting too much time and energy, under the premise that the peak power does not exceed the power rating limit of the spindle motor.

In addition to production requirements, the total spindle moment of inertia is another factor influencing the ESA. The ESA can be reduced by diminishing the total moment of inertia, which can be realized by reducing the mass of the spindle components. However, the mass reduction of spindle and pulley may lead to reduction of mechanical stiffness of the machine, and the rotor is not easy to be changed as it is part of the spindle motor. Thus the chuck is selected for mass reduction, in order to investigate the effect of the moment of inertia on the ESA. The self-weight of the ROTA NCL chuck is reported to be reduced by 35% in steel based body, and by up to 60% in an aluminum design in the future compared with conventional chucks of the same size (Schunk, 2011). This implies that the moment of inertia of the chuck could be reduced by up to 60%. If the moment of inertia of the chuck of the CK6153i CNC lathe is reduced by 60%, the moment of inertia of the spindle system drops from 0.3354 down to 0.2380 kg·m<sup>2</sup>. Accordingly, the peak power and energy consumption are reduced by 21.2% and 20.6%, respectively (see Fig. 8). Thus lightweight design of components of the spindle is an effective approach to reducing the ESA.

The wear and tear of the spindle system is a third factor influencing the ESA. In order to investigate this effect, two machines of the same type are selected to test the power of spindle acceleration. Both machines are CK6153i CNC lathes manufactured in December 2002, which have been used for over 10 years. The spindle rotation power and spindle acceleration power of CK6153i II are higher than those of CK6153i I (see Fig. 9). This variation in the power values could be explained by the variation of frictional torque of spindle system. The different ways of machine tool use and maintenance may cause various degrees of wear and tear of spindle components (e.g. bearings, gears, belts). This could lead to unequal frictional conditions on the two spindle system and cause such variation in spindle acceleration power. Therefore, less energy could be consumed if the wear and tear is reduced by proper use and maintenance of the spindle, such as spindle warm up, bearing lubrication and spindle housing cleaning. The warm up is that the spindle should be rotated for some time without load after it is started before conducting machining tasks. This can heat the

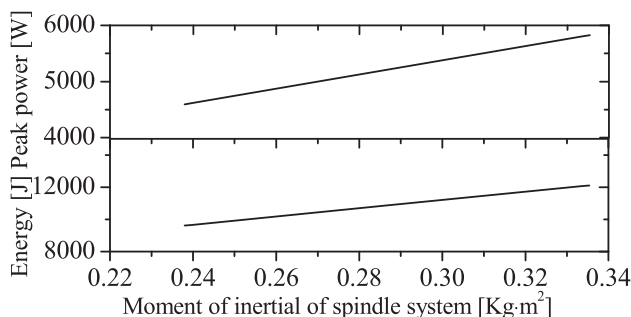


Fig. 8. Predicted peak power and energy consumption of spindle acceleration due to changes in moment of inertia. The Spindle was accelerated from 0 to 1500 rpm.

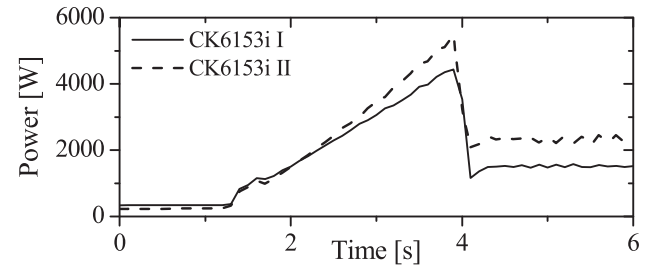


Fig. 9. Measured power of two machine tools of the same type during the spindle acceleration. CK6153i I is the machine used in the above research, CK6153i II is another machine of the same type. Spindles of all the two selected machines were accelerated from 0 to 1000 rpm.

bearings, bearing supports and the spindle shaft. The spindle bearings must be lubricated periodically to maintain adequate lubricating film between the balls and raceways of the bearing. The spindle housing should be cleaned periodically to remove the dirt and impurities in the lubricating oil. The aforementioned measures can help to reduce the wear and tear of the spindle system, thereby reducing the friction and energy consumption of the spindle system.

## 5.2. System level

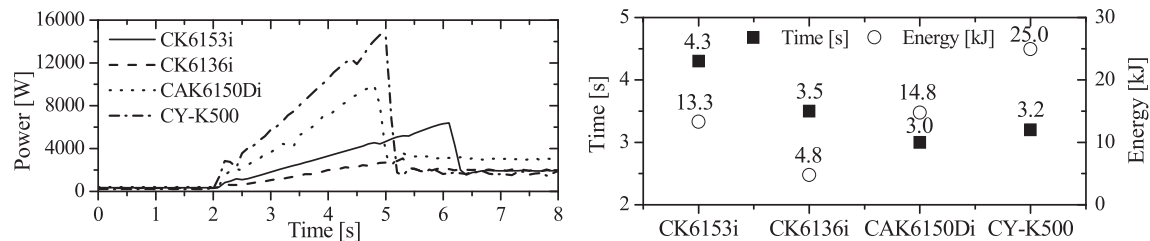
On the system level, machine selection can help to save energy in the parallel machine environment. The energy consumed by spindle system can be divided into load depended and load independent energy in machining. The former is the actual energy used when removing material, which is determined by the specific cutting energy multiplying the volume of material removed. The latter is the no-load energy consumed by spindle system, which consists of two parts: the energy consumed by spindle acceleration and energy consumed by spindle rotation. The total no-load energy consumption varies with different types of machines. In order to demonstrate this variation among different types of machine tools, experiments were conducted on four different CNC lathes to study the power characteristics of spindle rotation and spindle acceleration. The selected lathes included CK6153i, CK6136i, CAK6150Di and CY-K500. All the lathes are made in China. Comparing the obtained measured power data revealed that the power consumption ratio (slope of the graph) during spindle acceleration could vary significantly across different machines (see Fig. 10). The higher the slope, the larger amount of energy consumed by spindle acceleration. This energy consumption varied from 4.8 to 25.0 kJ, which could be explained by the variation of the moment of inertia of spindle system. As for the power of spindle rotation, it ranged from 1369 W for the CK6136i up to 1947 W for the CAK6150Di at the spindle speed of 1500 rpm.

The total no-load energy  $E_{NSP}$  can be formulated as:

$$E_{NSP} = E_{SA} + P_{SR}t_{SR} \quad (21)$$

where  $t_{SR}$  is the time for spindle rotation [s].  $E_{NSP}$  could be used to guide machine tool selection in order to save energy, since  $E_{NSP}$  accounts for a large percentage of total energy consumption during machining processes. The machine which consumes the minimum  $E_{NSP}$  is recommended to be selected for machining. For instance, for turning a cylindrical workpiece for 10 s at 1500 rpm,  $E_{NSP}$  were calculated to be 29.1 kJ, 18.5 kJ, 34.2 kJ and 39.0 kJ for CK6153i, CK6136i, CAK6150Di and CY-K500, respectively. If all the four lathes can be used to machine the workpiece, CK6136i is recommended to be selected for energy saving purpose.





**Fig. 10.** Measured power, time and energy of different types of machines tools during the spindle acceleration. Spindles of all the selected machines were accelerated from 0 to 1500 rpm.

Results suggest that the above energy saving approaches developed are quite promising. For instance, when the acceleration time is reduced by 30% for the CK6153i CNC lathe, the energy will be reduced by 10.6% (from 12,200 J to 10,906 J). By selecting proper machine for a machining task, the energy used can be dropped more than 50%, from 39.0 kJ (CY-K500) to 18.5 kJ (CK6136i). Also for lightweight design, reducing the weight of chuck can achieve 20.6% of energy reduction. Moreover, peak power is reduced, which leaves room for further shortening the acceleration time. When both the shortening acceleration time and lightweight design approaches are used, a better energy-saving effect could be achieved. For instance, when the moment of inertia is reduced to 0.2380 kg·m<sup>2</sup> and the acceleration time is preset to 1.96 s (30% reduction), calculation result showed that the ESA was reduced by about 30.6% (from 12,200 J to 8467 J) while the peak power did not increase compared to its original value. Therefore, joint implementation of these two approaches is effective to reduce the ESA while keeping the peak power under the motor power rating limit.

In industry, most of the above approaches are practical and easy to implement. For instance, instructions should be made to avoid unnecessary stopping and restarting of the spindle and achieve proper use and maintenance of the spindle, which can help increase the energy efficiency of machine tools. For shortening the acceleration time and machine tool selection, some calculations are needed to be conducted by technicians, such as calculation of peak power limits and total no-load energy of spindle system. The lightweight design approach may be relatively hard to implement due to redesign of machine tool. The weight reduction may lead to reduction of mechanical stiffness of the machines, which need further research to reduce the weight without deterioration of the machine tool stiffness.

## 6. Conclusion

Spindle acceleration frequently appears in CNC machining processes, which can lead to high power consumption in a short time period. Understanding the energy consumption characteristics provides the basis for the reduction of ESA. There has been some research on empirical modeling of the ESA of machine tools. However, coefficients in these models need to be acquired by conducting laborious experiments, and the models cannot help to reduce the ESA in machine tool design and use phase.

In the current work, a model to predict the ESA for CNC machine tools has been developed based on the principle of spindle mechanical transmission and motor control. The model incorporates two types of parameters: variable parameters and fixed parameters, which are functions of mechanical design and motor control parameters of the spindle system. Experiments were conducted to validate the effectiveness of the proposed model on a CK6153i CNC lathe. Results show that the predicted spindle acceleration power agrees well with the experimental data, and the average prediction

errors of time and energy of spindle acceleration are within 6%. The proposed models can be used to estimate the power, time and energy consumption of spindle acceleration without conducting laborious experiments.

The approaches for reducing the ESA include avoiding unnecessary stopping and restarting of the spindle, shortening the acceleration time, lightweight design, proper use and maintenance of the spindle and machine selection. The percentage of energy reduction by these approaches ranged from 10.6% to more than 50%. Moreover, joint implementation of the shortening the acceleration time and lightweight design approaches could achieve a 30.6% energy consumption reduction of spindle acceleration. In order to implement those approaches in industry, operating instructions should be provided to workers for proper use and maintenance of the spindle. In addition, some calculations are needed to be conducted by technicians, so that appropriate acceleration time is set in the inverter and the machine whose spindle consumes less no-load energy is selected, thereby reducing the time and energy of spindle acceleration as much as possible. The lightweight design approach is relatively hard to implement because further research is needed to guarantee the machine tool stiffness is not to be deteriorated.

The limitation of the study is that the motor slip is assumed to be zero, and the proposed models are only verified on CNC lathes. Further research can be conducted to improve the accuracy of the proposed model by considering the value of motor slip, and validate the models on more types of CNC machine tools, such as milling, drilling and grinding machines. Another research direction is the weight and stiffness optimization of spindle system for energy reduction.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.jclepro.2016.12.045>.

## Nomenclature

$D$	diameter of the cylinder part [m]
$D_1$	inside diameter of hollow cylinder part [m]
$D_2$	outer diameter of hollow cylinder part [m]
$E_{SA}$	energy consumption of spindle acceleration [J]
$E_{NSP}$	total no-load energy consumed by spindle system [J]
$J_e$	rotor inertia of spindle motor [ $\text{kg} \cdot \text{m}^2$ ]
$J_i$	total moment of inertia of the components in $i$ -th transmission link
$J_m$	equivalent moment of inertia for mechanical transmission system of spindle drive referred to spindle motor shaft [ $\text{kg} \cdot \text{m}^2$ ]
$J_{sp}$	equivalent moment of inertia for spindle drive system referred to spindle motor shaft [ $\text{kg} \cdot \text{m}^2$ ]
$L$	length or the thickness of the cylinder part [m]
$M$	mass of a cylinder part [kg]
$P_{SA}$	power of spindle acceleration [W]
$P_{SR}$	spindle rotation power [W]
$P_{\max}$	peak power of spindle acceleration [W]
$T_{SA}$	equivalent acceleration torque of the spindle drive system referred to spindle motor shaft [ $\text{N} \cdot \text{m}$ ]
$b_i$	load dependent power loss factor of $i$ -th transmission link
$f_i$	electrical frequency controlled by spindle inverter [Hz]
$f_{i1}$	inverter output frequency when the spindle speeds is $n_1$
$f_M$	maximum out frequency of the inverter [Hz]
$j_i$	transmission ratio of $i$ -th transmission link referred to spindle motor shaft
$k_A$	rise rate of the output frequency [Hz/s]
$m$	number of transmission links
$n$	spindle rotational speed [r/min]
$n_1$	initial spindle speed before acceleration [r/min]
$n_2$	final spindle speed after acceleration [r/min]
$n_M$	rotational speed of spindle motor [r/min]
$p$	number of pole pairs of the motor
$s$	motor slip
$t$	time of spindle acceleration [s]
$t_A$	acceleration time preset in spindle inverter [s]
$t_{SA}$	time period of spindle acceleration process [s]
$t_{SR}$	time for spindle rotation during a machining process [s]
$u_i$	drive ratio of $i$ -th drive chain to the spindle motor shaft
$\alpha$	angular acceleration of spindle [ $\text{rad/s}^2$ ]
$\alpha_M$	angular acceleration of spindle motor [ $\text{rad/s}^2$ ]
$\omega_M$	angular speed of spindle motor [rad/s]
$\rho$	material density of the spindle component [ $\text{kg/m}^3$ ]

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