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Characteristics of Additional Load Losses of Spindle System of Machine Tools*

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Abstract

Energy consumption of machine tool has drawn wide attention in recent years. The additional load losses of machine tools are of great importance for investigating the energy consumption of machine tools because those account for 15-20% of the cutting power and may even be up to nearly 30% of the cutting power in our researches. For lack of adequate understanding of the characteristics of additional load losses in the past, the additional load losses coefficient, defined as the ratio of additional load losses to cutting power, was regarded as a constant while the spindle speed was unchanged. However, it is discovered in our practical measurements that it is not so. In this paper, it proposes an additional load losses model based on power flow model, under the condition of the slip of spindle motor being small, in order to fully understand the characteristics of additional load losses. The characteristics of additional load losses include the relationship between additional load losses and cutting power, the relationship between additional load losses and spindle speed, and the relationship between additional load losses and cutting torque. Further more, an experimental system is developed to acquire the additional load losses through measuring cutting torque, spindle speed and input power of machine tool. As an example, several experiments are carried out on the CNC lathe by adjusting cutting parameters including spindle speed, feed rate and cutting depth. The experimental results show that the additional load losses coefficient varies with spindle speed and cutting torque, which can be fitted by a 1st order polynomial.

Key words: Machine Tool, Spindle System, Additional Load Losses, Energy Saving, Cutting Torque

Nomenclature:

α : Additional load loss coefficient of spindle system (Unitless);

b_m : Additional load loss coefficient of mechanical transmission of spindle system (Unitless);

I_1 : Stator current of induction motor (A);

I_2 : Load component of stator current (A);

I_m : Magnetizing component of stator current (A);

K_1 : Proportional coefficient of the rated power to the rated slip of electric machine (w);

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K_{st} : Stray load loss coefficient(w/A^2);

n : Spindle speed (Rpm);

P_{ad} : Additional load losses of spindle system (w);

P_{am} : Additional load losses of mechanical transmission (w);

P_c : Cutting power of machine tools (w);

P_{cu1} : Stator winding losses of electric machine (w);

P_{cu1-pc} : Stator winding losses of electric machine induced by cutting power (w);

P_{cu1-um} : Stator winding losses of electric machine induced by tare power of mechanical transmission (w);

P_{cu2} : Rotor losses of electric machine (w);

P_{cu2-pc} : Rotor losses of electric machine induced by cutting power (w);

P_{cu2-um} : Rotor losses of electric machine induced by tare power of mechanical transmission (w);

P_f : Friction losses of electric machine (w);

P_{fixed} : Fixed losses of electric machine (w);

P_{Fe1} : Stator core losses of electric machine (w);

P_i : Input power of spindle system (w);

P_{mec} : Mechanical power of electric machine (w);

P_r : Rated power of electric machine (w);

P_{shf} : Shaft power of induction motor (w);

P_{st} : Stray load losses of electric machine (w);

P_{st-pc} : Stray load losses of electric machine induced by cutting power (w);

P_{st-um} : Stray load losses of electric machine induced by tare power of mechanical transmission (w);

P_{um} : Tare power of mechanical transmission (w);

P_{vri} : Variable losses of electric machine (w);

P_{vri-um} : Variable losses of electric machine induced by tare power of mechanical transmission (w);

P_w : Windage losses of electric machine (w);

R_1 : Stator effective resistance (Ω);

R_1' : Stator effective resistance after conversion (Ω);

R_2' : Rotor effective resistance after conversion (Ω);

R_m : Core-loss resistance (Ω);

s : Slip of induction motor(Unitless);

s_r : Rated slip of induction motor(Unitless);

T_c : Cutting torque of the machine tool (N・m);

V : Stator line-to-neutral terminal voltage (Volts);

X_1' : Stator reactance after conversion (Ω);

X_2' : Stator reactance after conversion (Ω);

X_m : Magnetizing reactance (Ω);

ω : Spindle speed (Rad/s)

1. Introduction

Studying energy consumption of machine tool has been becoming one of hotspot issues in recent years (1-3). Manufacturing and related processes consume substantial amounts of energy and other resources, as a result, have a measurable impact on the environment (4-5). Reducing the energy consumption of machine tools can significantly improve the environmental performance of manufacturing processes and systems. Kordonowy(6) established the energy consumption model involving in loaded operation as well as unloaded operation to evaluate the energy efficiency using a constant tare power of the spindle. Vijayaraghavan and Dornfeld (1) applied event stream processing techniques to automatically monitor and analyze the energy consumption in manufacturing systems. Toenissen (3) characterized in detail the power consumption of a precision machine tool during various types of manufacturing activities, and estimated the power consumption of various machine tool components by empirical analysis.

The first step towards reducing energy consumption in machine tools and manufacturing systems is to understand and characterize their energy consumption(2). Generally, the energy consumption of spindle system is the majority of energy consumption of machine tool and varies instantly with various types of manufacturing activities (7). Therefore, the energy consumption of spindle system plays an important role in investigating the energy consumption of machine tool. Vijayaraghavan and Dornfeld (1) showed that the energy consumption of spindle system depended on the load (the cutting power) and increased with the increase of load. The machine tool efficiency can be defined as the ratio of necessary cutting power to consumed power which is absorbed from the power network by the spindle motor (8). Nevertheless, in their researches the additional load loss of spindle system has not been taken into consideration, which accounts for 15-20% of the cutting power [7] and may be up to 30% of the cutting power in our practical measurement.

However, the characteristics of the additional load losses of spindle system of machine tools have not been fully understood until today. In fact, it is a challenging task to fully investigate the characteristics of the additional load losses of spindle system of machine tools due to the following reasons:

(1).The spindle system of machine tool is composed of the electrical machine and the mechanical transmission, and the additional load losses of each part are complex[7];

(2).Even if the motorized spindle has developed and the mechanical transmission may be eliminated, the additional load loss of spindle system is complicated because the built-in motor introduces a great amount of heat into the spindle system as well as additional mass to the spindle shaft[9];

(3).It is invasive for machine tools to measure the additional load losses of each part. Once the machine tool has been setup, it is impossible to measure the additional losses of the spindle motor and the mechanical transmission, respectively.

(4).It is difficult to mathematically calculate the additional load losses because there are too many parameters of which some are unavailable in spindle system.

In the past, the additional load losses of electric motor and mechanical transmission drew wide attention, respectively. As to the former one, the additional losses of induction motor included [10-12] the stator winding losses, rotor losses and stray load losses. The Stator winding losses and rotor losses [10-12] were proportional to the resistance of the material and the square of the current. The stray losses[11, 13] arose from a variety of sources and were difficult to be either measured directly or calculated, but were generally proportional to the square of the rotor current [11]. Further more, the power losses of single phase induction motors driven by variable frequency were investigated [14].As to the latter one, the additional load losses of mechanical transmission were proportional to the load[7]. However, the researches integrating the electric motor and the mechanical transmission were rare, as we know presently. Liu et al.[7] remarked that the additional load losses was proportional to the cutting power and influenced by cutting torque and spindle speed. SHI et al.[15] established an energy flow model of spindle system driven by VVVF(variable voltage variable frequency) inverter and analyzed the additional load losses on every section of spindle system chain in the CNC machine tool. However, in their researches the additional load loss coefficient was considered as a constant for lack of the relationship between additional load losses and cutting power. To the best of the authors' knowledge, it is an open question that how to determine the relationship between additional load losses and cutting power at present. In the industrial application, the additional load losses coefficient was empirically chosen as a constant 0.15-0.25 for lathe [7].

In this paper, the characteristics of the additional load losses of spindle system of machine tools are investigated. An additional load losses model is proposed to investigate the characteristics of the spindle system which included following relationships: the relationship between additional load losses and cutting power; the relationship between additional load losses and cutting torque when assuming the spindle speed invariable; the relationship between additional load losses and spindle speed when the cutting torque was assumed invariable. With some parameters being unavailable, these relationship functions cannot be determined with theoretical model in practice, and then an experimental method is proposed to determine the relationship functions for convenience of industrial applications.

2. Additional load losses model for spindle system

2.1 Power flow model for the spindle system

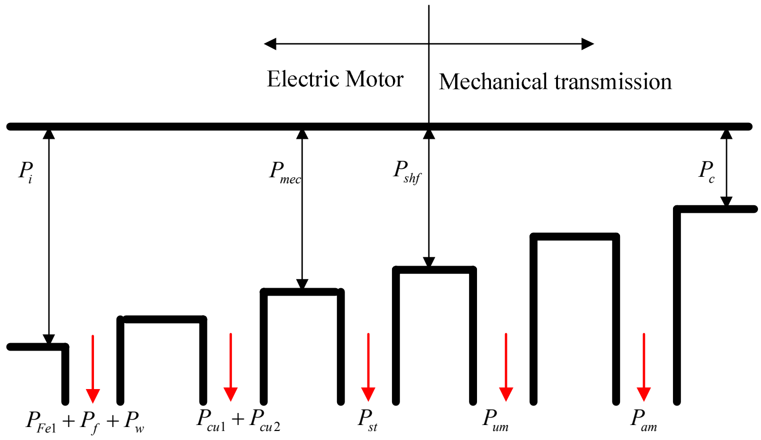

Fig.1. Power flow model for the spindle system of machine tool

The spindle system of machine tool consists of electrical machine and mechanical transmission. The power flow is shown in Fig.1 when the machine tool is in stable state. The input power flow is divided into eight parts as follows:

$$P_i = P_{Fe1} + P_f + P_w + P_{cu1} + P_{cu2} + P_{st} + P_{um} + P_{am} + P_c \quad (1)$$

The power loss of electrical motor is classified into two groups: the fixed load losses and the variable load losses. The fixed load losses, independent of load, include stator core losses as well as friction and wind age losses. The variable losses, dependent on load, include stator-winding losses, rotor losses and stray load losses(11-12). Therefore, the input power can be expressed as follows:

$$P_i = P_{fixed} + P_{vri} + P_{um} + P_c \quad (2)$$

In Eq. (2),

$$P_{fixed} = P_{Fe1} + P_f + P_w \quad (3)$$

$$P_{vri} = P_{cu1} + P_{cu2} + P_{st} + P_{am} \quad (4)$$

It should be noted that the tare power of the mechanical transmission is a load for the electrical machine but not for spindle system and only the cutting power is defined as load for the spindle system. Therefore, the variable load losses can be divided into two groups: the first group is the power losses, which are induced by the tare power of the mechanical transmission and classified into the tare power of the spindle system; the second group is named as additional load loss which is induced by the cutting power. That is,

$$P_{vri} = P_{vri-um} + P_{ad} \quad (5)$$

In Eq.(5),

$$P_{vri-um} = P_{cu1-um} + P_{cu2-um} + P_{st-um} \quad (6)$$

$$P_{ad} = P_{cu1-pc} + P_{cu2-pc} + P_{st-pc} + P_{am} \quad (7)$$

From Eq.(6)-Eq.(7)

$$
\begin{aligned}
P_{vri} &= P_{vri-um} + P_{ad} \\
&= (P_{cu1-um} + P_{cu1-pc}) + (P_{cu2-um} + P_{cu2-pc}) + (P_{st-um} + P_{st-pc}) + P_{am} \\
&= P_{cu1} + P_{cu2} + P_{st} + P_{am}
\end{aligned} \quad (8)
$$

If the machine tool is in air-cut, the input power will be defined as tare power. The tare power of spindle system can be gotten from Eq. (2) when the cutting power is zero.

$$P_u = P_{fixed} + P_{um} + P_{vri-um} \quad (9)$$

Therefore, the equation for the input power, the tare power and the additional load losses can be gotten from Eq. (2), Eq. (7) and Eq. (9).

$$P_i = P_u + P_{ad} + P_c \quad (10)$$

2.2 Additional load losses model for spindle system

The variable load losses are composed of variable load losses of electrical machine and mechanical transmission[7, 15]. The variable load losses of electrical machine consists of stator winding loss, rotor loss and stray load loss. The stator winding loss and rotor loss are functions of the square of the current times the resistance of stator and rotor[11-12], the stray load losses are generally proportional to the square of the rotor current [10]. The variable load losses of mechanical transmission are proportional to the load[7]. According to single-phase equivalent circuit for an induction motor shown in Fig.2 [16], the variable load losses of an induction motor can be expressed according to Eq.(8)

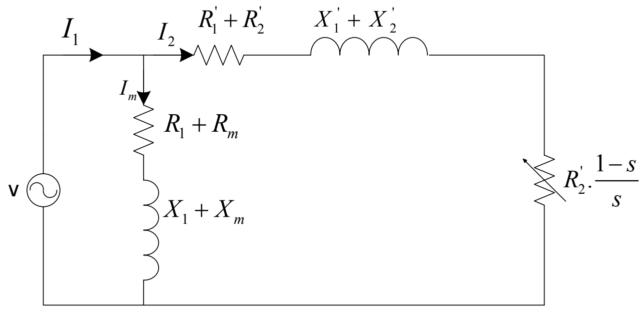

Fig.2 Single-phase equivalent circuit for an induction motor[16]

$$P_{veri} = P_{cu1} + P_{cu2} + P_{st} + P_{am} = 3I_2^2\left(R_1^{'} + R_2^{'}\right) + 3K_{st}I_2^2 + b_m P_c \quad (11)$$

The mechanical power of electrical machine can be calculated by the following equation:

$$P_{mec} = 3I_2^2 R_2^{'} \frac{1-s}{s} \quad (12)$$

$$P_c = P_{shf} - P_{um} - P_{am} = (P_{mec} - 3K_{st}I_2^2) - P_{um} - b_m P_c \quad (13)$$

Taking Eq. (12)-(13) into Eq. (11), we can get

$$P_{veri} = \frac{(R_1^{'} + R_2^{'} + K_{st})\left[(1+b_m)P_c + P_{um}\right]}{R_2^{'}} \frac{s}{1 - \frac{R_2^{'} + K_{st}}{R_2^{'}} s} + b_m P_c \quad (14)$$

Taking advantage of the nearly linear relationship between motor slip and load in induction motor [10], we can get

$$P_{shf} = K_1 s \quad (15)$$

Wherein,

$$K_1 = \frac{P_r}{s_r} \quad (16)$$

$$P_{shf} = P_{um} + (1 + b_m)P_c \quad (17)$$

Because the slip is a small positive value, usually 2%-5%[16], we can obtain

$$\frac{R_2^{'} + K_{st}}{R_2^{'}} s \langle\langle 1 \quad (18)$$

$$\frac{s}{1 - \frac{R_2^{'} + K_{st}}{R_2^{'}} s} \cong s \quad (19)$$

Therefore

$$\begin{aligned} P_{veri} &= \frac{\left(R_1^{'} + R_2^{'} + K_{st}\right)}{R_2^{'} K_1}\left[(1 + b_m)P_c + P_{um}\right]^2 + b_m P_c \\ &= \frac{\left(R_1^{'} + R_2^{'} + K_{st}\right)}{R_2^{'} K_1}(1 + b_m)^2 P_c{}^2 + \frac{2\left(R_1^{'} + R_2^{'} + K_{st}\right)P_{um} + R_2^{'} K_1 b_m}{R_2^{'} K_1} P_c \\ &+ \frac{\left(R_1^{'} + R_2^{'} + K_{st}\right)}{R_2^{'} K_1} P_{um}^2 \end{aligned} \quad (20)$$

In the same manner, we can get the variable load losses induced by tare power of mechanical transmission

$$P_{veri-um} = \frac{(R_1^{'} + R_2^{'} + K_{st})}{R_2^{'} K_1} P_{um}^2 \quad (21)$$

From Eq. (5), Eq. (16) and Eq. (17), the additional load losses can be obtained:

$$P_{ad} = \frac{\left(R_1^{'} + R_2^{'} + K_{st}\right)}{R_2^{'} K_1}(1 + b_m)^2 P_c{}^2 + \frac{2\left(R_1^{'} + R_2^{'} + K_{st}\right)P_{um} + R_2^{'} K_1 b_m}{R_2^{'} K_1} P_c \quad (22)$$

If we define the ratio of additional losses to load as the additional load loss coefficient, then the additional load loss coefficient can be expressed as,

$$\alpha = \frac{\left(R_1^{'} + R_2^{'} + K_{st}\right)}{R_2^{'} K_1}(1 + b_m)^2 P_c + \frac{2\left(R_1^{'} + R_2^{'} + K_{st}\right)P_{um} + R_2^{'} K_1 b_m}{R_2^{'} K_1} \quad (23)$$

Because the load P_c is affected by spindle speed and cutting torque ($P_c = T_c \omega$), the additional load losses should vary with spindle speed and cutting torque.

When the spindle speed or the cutting torque is invariable, the additional load losses and additional load loss coefficient should change as follows,

$$P_{ad}=\begin{cases}\dfrac{(R_1^{'}+R_2^{'}+K_{st})(1+b_m)^2C_0^2}{R_2^{'}K_1}T_c^2+\dfrac{2(R_1^{'}+R_2^{'}+K_{st})P_{um}C_0+R_2^{'}K_1b_mC_0}{R_2^{'}K_1}T_c & \omega=C_0\\ \dfrac{(R_1^{'}+R_2^{'}+K_{st})(1+b_m)^2C_1^2}{R_2^{'}K_1}\omega^2+\dfrac{2(R_1^{'}+R_2^{'}+K_{st})P_{um}C_1+R_2^{'}K_1b_mC_1}{R_2^{'}K_1}\omega & T_c=C_1\end{cases} \quad (24)$$

$$\alpha=\begin{cases}\dfrac{(R_1^{'}+R_2^{'}+K_{st})(1+b_m)^2C_3}{R_2^{'}K_1}T_c+\dfrac{2(R_1^{'}+R_2^{'}+K_{st})P_{um}+R_2^{'}K_1b_m}{R_2^{'}K_1} & \omega=C_3\\ \dfrac{(R_1^{'}+R_2^{'}+K_{st})(1+b_m)^2C_4}{R_2^{'}K_1}\omega+\dfrac{2(R_1^{'}+R_2^{'}+K_{st})P_{um}+R_2^{'}K_1b_m}{R_2^{'}K_1} & T_c=C_4\end{cases} \quad (25)$$

In Eq. (24) and Eq. (25), the symbols C_1, C_2, C_3 and C_4 are some constants.

From the Eq.(22) and the Eq.(23), it can be shown that the additional load loss is a 2nd order function of the load and the additional load loss coefficient is a first-order function of the load. In addition, the variations of additional load loss and coefficient with spindle speed or cutting torque are shown as Eq. (24)-(25), respectively.

2.3 Measurement principle for additional load losses of spindle system

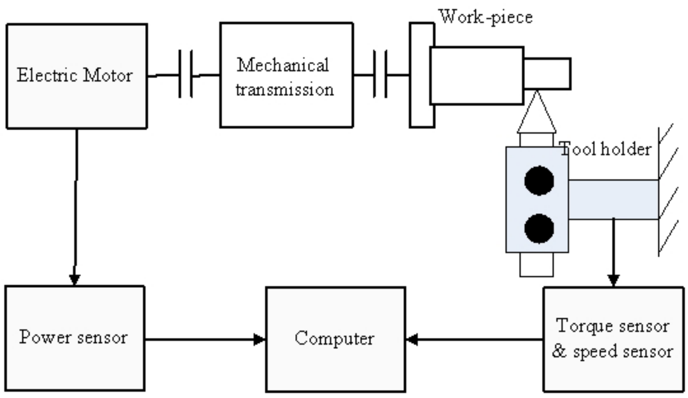

Fig.3. Schemes of the measurement system

Though additional load losses and additional load loss coefficient can be determined with Eq.(22) and Eq.(23), it is difficult indeed to obtain these functions because there are too many parameters of which some are unavailable such as damping coefficient b_m, stray load loss coefficient K_{st}. However, we can simply get these functions by experiment. The following equations can be gotten from Eq. (10),

$$P_{ad}=P_i-P_u-P_c \quad (26)$$

$$\alpha=\frac{P_i-P_u-P_c}{P_c} \quad (27)$$

If the input power, the tare power and the cutting power in Eq. (26)-(27) are measured, the relationship functions can be easily obtained from the experiment data by polynomial fitting method.

3. Materials and experiment procedure

3.1 Measurement system for additional load losses

The measurement system is developed to obtain the additional load losses through measuring the three signals: input power, cutting torque, and spindle rotation speed. Figure 3 shows the schematic structure of the measurement system. The measurement system adopts the wireless torque sensor TQ201 to measure the torque on the tool holder and the cutting power can be calculated indirectly. In addition, TQ201 can measure the spindle speed by hall switch in the sensor. The power transducer ED9033A is used to measure the 3-phase voltage, current, and active power in RMS. Detailed information about the ED9033A and TQ201 can be available at http://www.sdlckj.comand http://www.beetech.cn.

3.2 Materials and cutting conditions

A number of cutting experiments were conducted on a CNC lathe (CJK6136, Chongqing No.2 machine tool woks Co., Ltd, China). The specifications of machine tools and cutting tools are listed as follows:

- In the CNC lathe, the spindle motor is a 3-phase induction motor, in which the rated power is 5.5kw and the rated slip is 5%; the spindle speed range is from 45 rpm to 2100 rpm;
- The cutting tool (Zhuzhou cemented carbide cutting tools Co., Ltd, China) is a 90 degrees extern-turning tool; the cutter insert material is GB: YT15 (ISO: P10) and the dimension of the tool holder is 18mmx18mmx150mm.
- The coolant is dry;
- The work piece is a 45# steel bar with the diameter of 79mm and the length of 400mm.

The cutting experiments were undertaken in different cutting conditions shown in table 1.

Table1. Cutting condition details for experiments

Spindle speed(rev/min)	Feed rate(mm/rev)	Cutting depth(mm)
100	0.286 0.260 0.241 0.198 0.153 0.1	2.5 2 1.5 1 0.5
200	0.286 0.260 0.241 0.198 0.153 0.1	2.5 2 1.5 1 0.5
300	0.286 0.260 0.241 0.198 0.153 0.1	2.5 2 1.5 1 0.5
500	0.286 0.260 0.241 0.198 0.153 0.1	2.5 2 1.5 1 0.5
600	0.286 0.260 0.241 0.198 0.153 0.1	2.5 2 1.5 1 0.5
700	0.286 0.260 0.241 0.198 0.153 0.1	2.5 2 1.5 1 0.5
900	0.286 0.260 0.241 0.198 0.153 0.1	2.5 2 1.5 1 0.5

4. Results and discussion

4.1 Relationship between the additional load losses and the cutting power, and relationship between the additional load losses and the cutting power

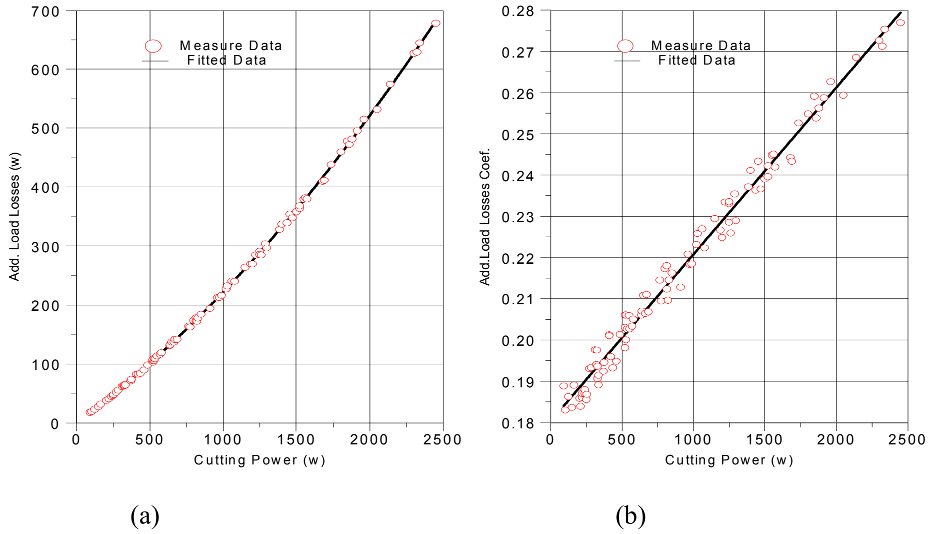

Fig.4.Additional load losses curve and curve of additional load loss coefficient with respect to the cutting power: (a) Additional load losses function, as a second order function of cutting power; (b) Additional load loss coefficient, as a 1st order function of cutting power

The additional load losses and the additional load loss coefficient are calculated from the experimental data of the input power, the tare power and the cutting power using Eq.(9) and Eq.(10). According to Eq.(22)-(23), the additional load losses can be fitted by a second order polynomial function and additional load loss coefficient can be fitted by a first order polynomial function by the measured data (shown in Fg.4). For the spindle system of the CNC lathe CJK6136, the relationship functions are listed as follows:

$$P_{ad} = 4.0\times10^{-5}\cdot P_c^2 + 0.1807\cdot P_c \tag{28}$$

$$\alpha = 4.0\times10^{-5}\cdot P_c + 0.1807 \tag{29}$$

4.2 Additional load losses varies with spindle speed and cutting torque, respectively.

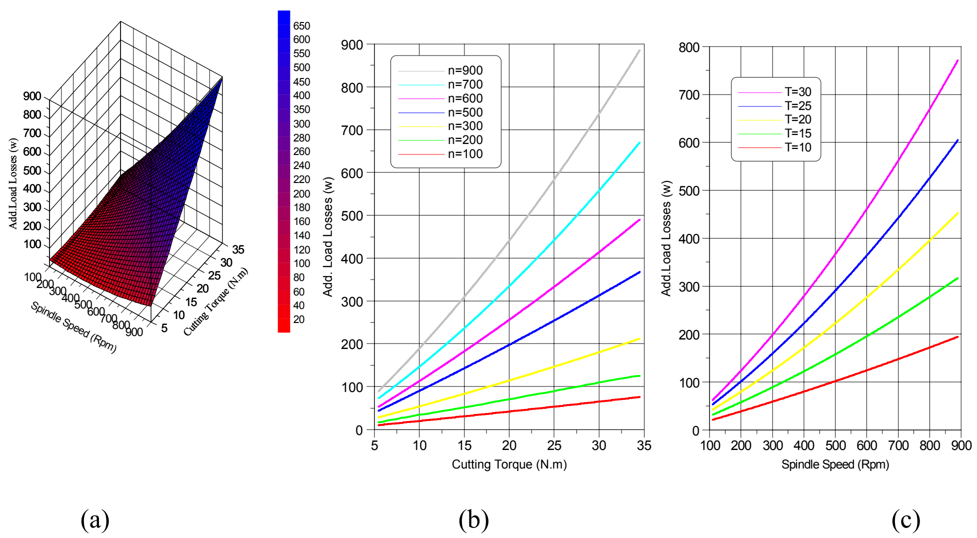

Fig.5.Additional load losses vary with spindle speed and cutting torque: (a) Additional load losses surface vs. spindle speed & cutting torque; (b) Additional load losses vs. cutting torque for seven spindle speeds; (c) Additional load losses vs. spindle speed for five cutting torques

The additional load losses are calculated from the experimental data of the input power, the tare power and the cutting power using Eq. (26). On the whole, the additional load losses increase with the increase of spindle speed and cutting power, which is depicted in Fig.5 (a).

When the spindle speed is determined, the relationship between the additional load loss power and cutting torque (Fig.5 (b)), is fitted by using second order polynomial function and listed as follows

$$P_{ad} = \begin{cases} 4.889\times10^{-3}\cdot T_c^{\,2} + 1.998\cdot T_c & n = 100rpm \\ 1.309\times10^{-2}\cdot T_c^{\,2} + 3.269\cdot T_c & n = 200rpm \\ 3.168\times10^{-2}\cdot T_c^{\,2} + 5.085\cdot T_c & n = 300rpm \\ 8.182\times10^{-2}\cdot T_c^{\,2} + 8.172\cdot T_c & n = 500rpm \\ 1.127\times10^{-1}\cdot T_c^{\,2} + 10.17\cdot T_c & n = 600rpm \\ 1.980\times10^{-1}\cdot T_c^{\,2} + 12.71\cdot T_c & n = 700rpm \\ 3.508\times10^{-1}\cdot T_c^{\,2} + 15.80\cdot T_c & n = 900rpm \end{cases} \qquad (30)$$

In the same manner, the relationship between the additional load losses and the spindle speed with cutting torque as a constant (Fig.5(c)), fitted by using second order polynomial function, can also be found.

$$P_{ad} = \begin{cases} 3.820\times10^{-5}\cdot n^2 + 0.1838\cdot n & T_c = 10N\cdot m \\ 1.028\times10^{-4}\cdot n^2 + 0.2638\cdot n & T_c = 15N\cdot m \\ 1.640\times10^{-4}\cdot n^2 + 0.3622\cdot n & T_c = 20N\cdot m \\ 2.539\times10^{-4}\cdot n^2 + 0.4533\cdot n & T_c = 25N\cdot m \\ 3.522\times10^{-4}\cdot n^2 + 0.5545\cdot n & T_c = 30N\cdot m \end{cases} \qquad (31)$$

4.3 Additional load loss coefficient varies with the spindle speed and the cutting torque, respectively

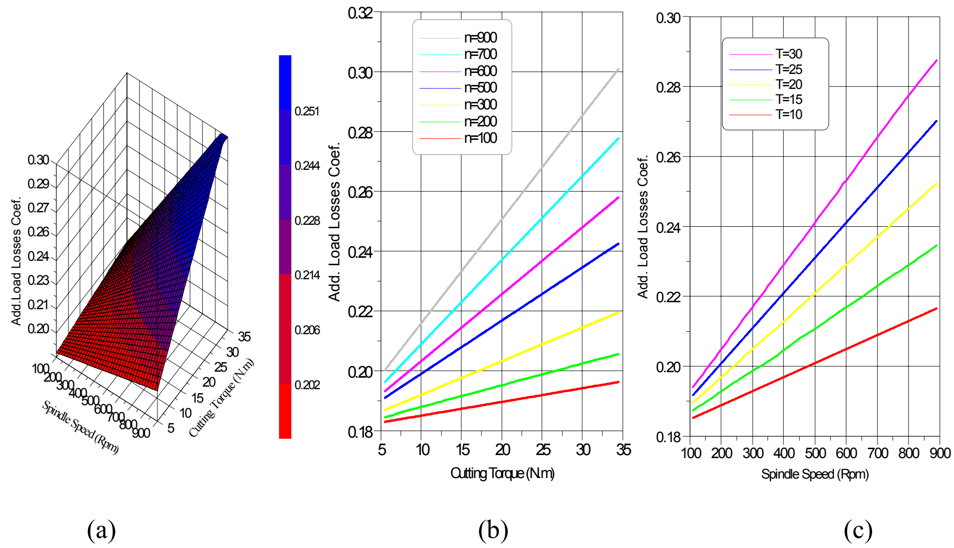

Fig.6. Additional load loss coefficient varies with spindle speed and cutting torque: (a) Additional load loss coefficient varies with spindle speed and cutting torque; (b) Additional load loss coefficient varies with cutting torque for seven spindle speeds, (c) Additional load loss coefficient varies with spindle speed for five cutting torques

Overall, the additional load loss coefficient increase as spindle speed increases and cutting power increases, which is depicted in Fig.6 (a). Since the cutting torque and the spindle speed affect the cutting power, the cutting torque and the spindle speed should influence the additional load loss coefficient. Therefore, it is necessary to study the rule that how the cutting torque and the spindle speed affect the additional load loss coefficient. The method, same as the one for analyzing the relationship of the additional load losses and cutting torque, is taken again to decide the relationship of the additional load loss coefficient and cutting torque.

The relationship of the additional load loss coefficient and cutting torque (Fig.6 (b)), which is fitted by using first order polynomial function at the given spindle speed, is shown below.

$$\alpha = \begin{cases} 4.422\times10^{-4}\cdot T_c + 0.1807 & n = 100rpm \\ 7.236\times10^{-4}\cdot T_c + 0.1807 & n = 200rpm \\ 1.126\times10^{-3}\cdot T_c + 0.1807 & n = 300rpm \\ 1.809\times10^{-3}\cdot T_c + 0.1807 & n = 500rpm \\ 2.251\times10^{-3}\cdot T_c + 0.1807 & n = 600rpm \\ 2.814\times10^{-3}\cdot T_c + 0.1807 & n = 700rpm \\ 3.497\times10^{-3}\cdot T_c + 0.1807 & n = 900rpm \end{cases} \quad (32)$$

The relationship of the additional load loss coefficient and the spindle speed for constant cutting torques (shown in Fig.6(c)), fitted by using a first order polynomial function, can be similarly found.

$$\alpha = \begin{cases} 4.012\times10^{-5}\cdot n + 0.1807 & T_c = 10N\cdot m \\ 6.053\times10^{-5}\cdot n + 0.1807 & T_c = 15N\cdot m \\ 8.042\times10^{-5}\cdot n + 0.1807 & T_c = 20N\cdot m \\ 1.005\times10^{-4}\cdot n + 0.1807 & T_c = 25N\cdot m \\ 1.024\times10^{-4}\cdot n + 0.1807 & T_c = 30N\cdot m \end{cases} \quad (33)$$

5. Conclusions

To fully understand the characteristics of the additional load losses of the spindle system of machine tools, the additional load losses model of spindle system of machine tool is proposed and experiments are undertaken on a CNC lathe. From the results of theoretical analyses and the experiments, the following observations are made.

(1) After linearizing the power flow model Eq.(14) for the spindle system of machine tool under the condition that the slip of spindle motor is very small, the characteristics of the additional load losses of the spindle system of machine tools are obtained as Eq. (22)-Eq. (25). From the Eq. (22)-Eq. (25), the additional load loss coefficient is a first order function of the cutting power, which modifies the previous proportional relationship between the additional load losses and the cutting power.

(2) From the experiment results on the CNC lathe, the additional load losses is a 2^{nd} order function of the cutting power, and the additional load loss coefficient is a first order function of the cutting power. Further more, the additional load losses is a 2^{nd} order function of cutting torque or spindle speed when the other one is assumed invariable, and the additional load loss coefficient is a 1^{st} order function of cutting torque or spindle speed when the other one is assumed invariable.

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