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Influence Ruleson on Natural Frequency and Input Power of Y-axis Feeding System in Horizontal Machining Center

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Abstract: Some horizontal machining center with the structural characteristics of two columns and a vertical shifting worktable, Y-axis feeding system should meet the requirements of large load bearing, high speed, high precision and low energy consumption. The proper selection of design and operating parameters is the key of ensuring accuracy and energy consumption of machine tools. With analyzing the structure and the performance feature of horizontal machining center with double-column vertical shifting worktable, dynamic equation of Y-axis feeding system was established and the rationality of the dynamic model was verified by combining with finite element analysis. The influence rules of design parameters (screw diameter, worktable mass and worktable position) on natural frequency were analyzed. The influence mechanisms of input power during the system operation process were analyzed, calculation model of input power was presented and the influences of design and operating parameters on input power were analyzed. The research results are valuable for high-precision and low-energy consumption Y-axis feeding system designing.

Key words: Vertical shifting worktable, feeding system, Y-axis, natural frequency, energy consumption

INTRODUCTION

There are different layout form between traditional horizontal machining center and the horizontal machining center with two columns and vertical shifting worktable, in the latter type of horizontal machining center, the double columns are arranged in the front of the machine tool and the worktable can move the double columns. Y-axis feeding system bears the weight of the worktable and work piece about 2 tons, the maximum acceleration reaches 8 g m^{-2} and the high precision requirement should be satisfied synchronously. The dynamic characteristics of horizontal machining center with vertical shifting worktable are related closely with the precision and energy consumption of machine tool.

The feeding system is the key subsystem of CNC machining center, the feeding speed and acceleration are the important indicators of measuring machine tool performance. The dynamic features of the feeding system influence obviously the natural frequency, precision, repeated positioning precision, etc., of machine tool (Hsieh *et al*., 2007). On the other hand, the energy consumption of machine tool has great influences on the whole energy consumption of manufacture. The feeding system is the main energy source of machine tool (Mori *et al*., 2011).

Recently, some researchers researches on the dynamic characteristic of feeding system and some analytical models and methods were presented. Ding *et al*. (2011) and Whalley *et al*. (2005) established distributed-lumped parametric model to describe the dynamic characteristics and analyzed the influence of the ball screw space distribution of feeding system on the dynamic characteristics. Parpala (2009) and Zaeh *et al*. (2004) analyzed natural frequency and mode of vibration of feeding system using FEM technology. Vicente *et al*. (2012) established dynamic model of feeding system using Lagrange equation. Zhou *et al*. (2011) analyzed the influence of design parameter on the first three natural frequency of feeding system. Although, above researchers have researched on the dynamic behavior of the feeding system and some models were bought forward, with the difference in layout form between traditional horizontal machining center and the horizontal machining center with two columns and vertical shifting worktable, the dynamic characteristics related to the latter type of machine tool should be analyzed further and the influence of design parameter, such as screw diameter and load parameters, such as worktable mass, worktable position, etc., on natural frequency should be determined.

Recently, studies on the energy consumption of the machine tool parts focuses on the spindle and main drive

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system (Zein *et al*., 2011). Shi (2009) and Shi *et al*. (2010) established power equilibrium equation for variable frequency spindle system of CNC machine. Abele *et al*. (2011) analyzed the energy consumption and illustrated the potential of energy consumption of spindle system. However, few of researches have been done to analyze the influence of the design parameters and operating parameters on the energy consumption of feeding system. The Y-axis feeding system bears the weight above 2 tons and should meet the requirements of high velocity and high acceleration synchronously, the consumed energy during operation process can reach 20~30 kW, it is necessary to decease energy consumption level of Y-axis feeding system.

Aiming at increasing natural frequency and decreasing energy consumption of feeding system concurrently, the dynamic model will be built to analyze the influence of design parameters on dynamic characteristics, the energy consumption factors will be discussed and the mapping relationships between design parameters, operation parameters and energy consumption will be determined.

CALCULATION ON NATURAL FREQUENCY OF FEEDING SYSTEM

Dynamical model of Y-axis feeding system: The Y-axis feeding system model of horizontal machining center with vertical shifting worktable is shown in Fig. 1. Two ball screws drive the worktable and work piece to move reciprocating. It is convenient for assembling and unloading work piece.

To analyze the dynamic characteristics of feeding direction, the multi degree of freedom model is built: The screw is divided into s units; the part between servo motor and screw is divided into r units and then the multi degree of freedom model is determined. The normal pressure from the rollaway nest to the ball can be divided into axial force R_Z and tangential force along the circumference R_T, as shown in Fig. 2:

$$R_Z = k_{sl}\left(x - x_i - \frac{P_h}{2\pi}\theta_i\right) \tag{1}$$

$$\begin{aligned} R_T &= R_Z \bullet \tan\alpha = \tan\alpha \bullet k_{sl}\left(x - x_i - \frac{P_h}{2\pi}\theta_i\right) \\ &= \frac{P_h}{\pi d}k_{sl}\left(x - x_i - \frac{P_h}{2\pi}\theta_i\right) \end{aligned} \tag{2}$$

where, k_{sl}-axial stiffness of screw nut pair (N μm^{-1}), x-displacement of worktable (mm), x_j, θ_i-axial displacement and corner of the ith section (mm, rad), P_h-lead of the ball screw (mm), α- lead angle the ball screw (rad), d-diameter of the ball screw (mm).

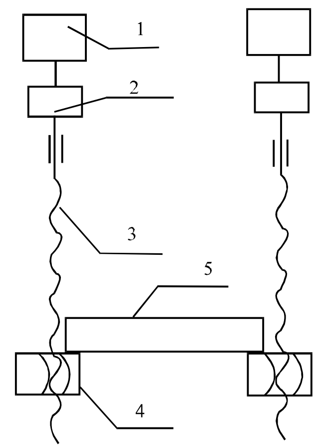

Fig. 1: Y-axis feeding system structural diagram (1) Servo motor, (2) Coupling, (3) Screw, (4) Nut, (5) Worktable

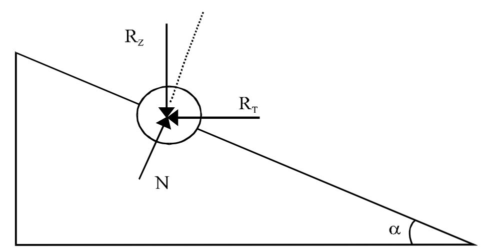

Fig. 2: Screw nut pair force diagram

The dynamic stiffness along feeding direction (Y-direction) is weak, this study focuses on the dynamic characteristics of Y-axis. The worktable can be expressed as concentrated mass along feeding direction. For the antifriction bearing, axial stiffness and damping, torsional damping should be taken into account. The nut pair can be simplified as the axial stiffness, damping and torsional damping, the dynamic model as shown in Fig. 3.

$$\begin{aligned} m_i\ddot{x}_i &= k_z\left(x_{i-1} - x_i\right) + k_z\left(x_{i+1} - x_i\right) \\ &+ k_{sl}\left(x - x_i - \frac{P_h}{2\pi}\theta_i\right) - m_i g \end{aligned} \tag{3}$$

where, m_i-the mass of ith section screw (kg), k_Z-the axial tension and compression stiffness between each two sections of ball screw (N m^{-1}):

$$kgJ_i\ddot{\theta}_i = k_n\left(\theta_{i-1} - \theta_i\right) + k_n\left(\theta_{i+1} - \theta_i\right) + R_T \bullet \frac{d}{2} \tag{4}$$

where, J_i-the rotational inertia of ith section screw (kg•m^2), k_n-the torsional rigidity between each two sections of ball screw (N m^{-1}):

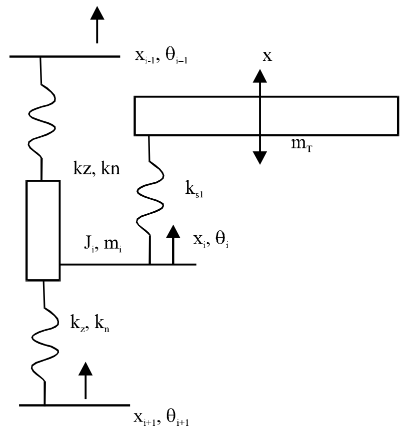

Fig. 3: Dynamical model

Table 1: First six natural frequencies of feeding system

Order	ω_1	ω_2	ω_3	ω_4	ω_5	ω_6
Frequency (Hz)	91.2	179.6	181.2	182.4	184.5	226.8

Table 2: Natural frequency

Order	ω_1	ω_2	ω_3	ω_4	ω_5	ω_6
Frequency (Hz)	89.3	182.6	182.7	182.8	182.9	229.2

$$m_T\ddot{x} = k_{s1}\left(x_i - x - \frac{P_h}{2\pi}\theta_i\right) - m_T g \tag{5}$$

where, m_T-the mass of worktable (kg):

$$J\ddot{q} + Kq = 0 \tag{6}$$

Ignoring constant terms $m_i g$ and $m_T g$, the differential equation of undamped vibration can be written as matrix form:

$$J = \begin{bmatrix} J_1 & & & & & & & & \\ & \ddots & & & & & & & \\ & & J_r & & & & & & \\ & & & J_{r+1} & & & & & \\ & & & & \ddots & & & & \\ & & & & & J_{r+s} & & & \\ & & & & & & m_1 & & \\ & & & & & & & \ddots & \\ & & & & & & & & m_s \\ & & & & & & & & & m_T \end{bmatrix}$$

$$\theta = \{\theta_1 \cdots \theta_r \quad \theta_{r+1} \cdots \theta_{r+i} \cdots \theta_{r+s} \quad x_1 \cdots x_i \cdots x_s \quad x\}^T$$

$$J_1 = J_M$$

where, J_M is rotational inertia of motor (kg•m^2), $\theta_1 = \theta_M$, θ_M is the angle of the motor rotor (rad), k_y^n, n in k_y^Z denotes torsional rigidity, z indicates axial tension and compression stiffness, the subscript expresses the node number:

$$K = \begin{bmatrix} k_1^n & -k_1^n & & & \\ -k_1^n & \ddots & \ddots & & \\ & \ddots & k_{r+i-1}^n + k_{r+i}^n + \left(\frac{P_h}{2\pi}\right)^2 k_{sl} & -k_{r+i-1}^n & \\ & & -k_{r+i-1}^n & \ddots & \ddots \\ & & & \ddots & \left(\frac{P_h}{2\pi}\right)^2 k_{sl} \end{bmatrix}$$

Verification of the dynamical model: According to the requirement of load, velocity and acceleration, the initial parameters of feeding system are determined. The rationality of dynamical model can be verified combining finite element analysis. According the dynamic model, the first six natural frequencies can be obtained, as shown in Table 1.

Modal analysis is developed using ANSYS and the natural frequencies of according vibration model (axial direction, revolution and corresponding combination) are calculated as shown in Table 2.

According to Table 1 and 2, the calculation result based on dynamic model is in accordance with the result of FEA, the rationality of dynamical model can be verified.

INFLUENCE OF DESIGN PARAMETERS ON NATURAL FREQUENCY

The Y-axis feeding system of horizontal machining center with vertical shifting worktable differs from the conventional machine tool in two ways: (1) Larger diameter of the screw to meet stiffness requirements, because of larger axial bearing, (2) The worktable location influence both the load-download and the natural frequency of system. According to the dynamic model, the influence of both the design parameters (screw diameter, screw lead, motor rotating inertia) and the load parameters (worktable mass, worktable position) on the natural frequency will be determined.

It's worth noting that the change of worktable position l is related to screw tension and compression stiffness k_Z, torsional rigidity k_n and affect the natural frequency of system. There are the following relations between k_Z k_n and l:

$$k_z = \frac{4l}{\pi E d^2} \tag{7}$$

$$k_n = \frac{\pi G d^4}{32l} \tag{8}$$

where, E is elasticity modulus of materials, d is screw thread bottom diameter, G is shear modulus of elasticity of material.

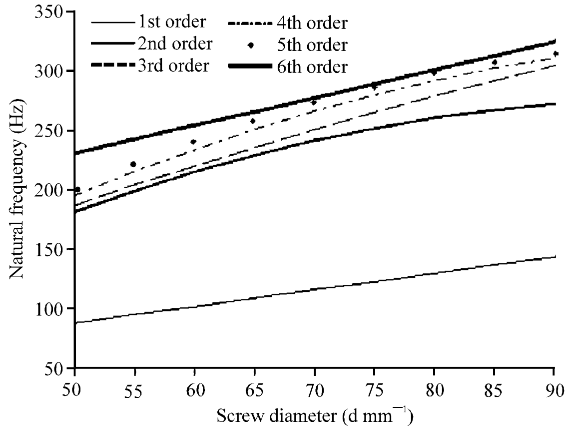

Fig. 4: Influence of screw diameter on natural frequency

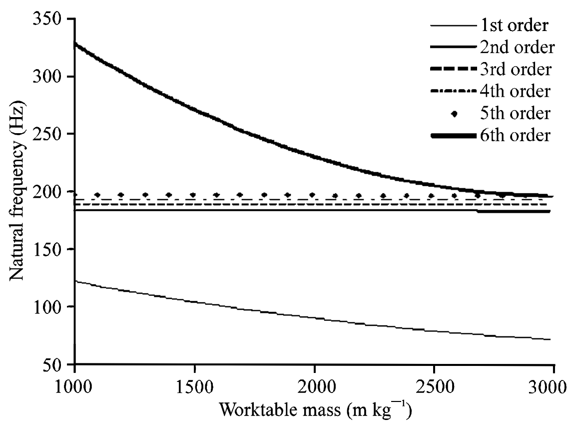

Fig. 5: Influence of worktable mass on natural frequency

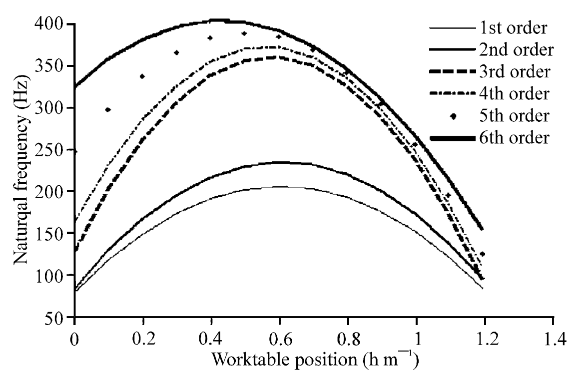

Fig. 6: Influence of worktable position on natural frequency

The screw diameter, worktable mass and worktable position have great influence on the natural frequency. Figure 4-6 correspond to the influence rules of screw diameter, worktable mass and worktable position on the natural frequency of system, respectively.

According to the analysis result, the natural frequency of feeding system is inversely proportional to the worktable mass and it is in directly proportion to screw diameter. When the worktable is in the middle of the screw, the natural frequency reaches the largest value, with the worktable moving up and down, the natural frequency gradually reduces.

INFLUENCE OF DESIGN AND OPERATING PARAMETERS ON ENERGY CONSUMPTION

Energy consumption factor of the feeding system: Theorem of kinetic energy is the basic law of the mechanical system operation. It points out that the work which is done by the force (the total force upon the object) on the object is equal to change of the kinetic energy of the object:

$$dE = \sum \delta W_i \tag{9}$$

where, dE denotes change of the kinetic energy, δW_i indicates the work of force F_i.

According to work-energy theorem, the power equation of the mechanical system is obtained:

$$P_I = dE/dt + P_O + P_U \tag{10}$$

where, P_J denotes input power, dE/dt is kinetic energy change rate, P_O is useful power, P_U is useless power which is caused of the friction.

The operation cycle of feeding system involves three operation states: Start, stable operation and stop. Different operation states correspond to different P_E, as shown in Fig. 7, the kinetic energy of system increases in start stage, $P_E>0$, remains unchanged or changes a little in the stable operation stage, $P_E \approx 0$, deceases in the stop stage, $P_E<0$.

Considering differences in different operating states, the energy consumption composition of the feeding system model is built, as shown in Fig. 8.

P_{i1} and P_{i2} corresponds, respectively to the input power a set of drive system. P_S P_h P_l, respectively correspond to starting state, heavy cutting state and light cutting state. The relationship between P_S P_h P_l and P_{i1} is addition in proportion, the time proportion of starting state, heavy cutting state and light cutting state are, respectively a, b and c%. When different kinds of parts are processed, the time proportion of operating states is different. For example, in the manufacturing process of automobile engine block and cylinder head, a, b and c%, respectively correspond to 30, 10 and 60%. P_{sp} P_{hp} P_{lp}, respectively correspond to the power caused by the preload of screw nut pair in the high-speed feeding state,

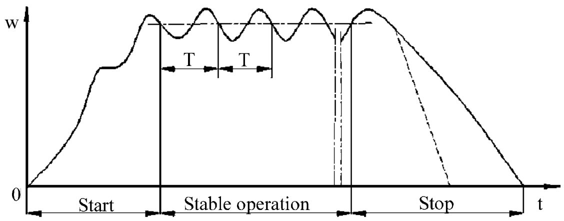

Fig. 7: Operating states of feeding system

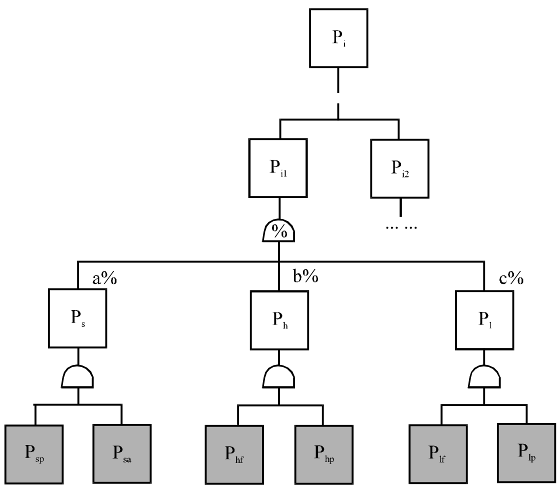

Fig. 8: Energy consumption factor model

heavy cutting state and light cutting state. P_{sa} corresponds to the power caused by acceleration movement of the feeding system, worktable and work piece. P_{hf} P_{lf}, respectively correspond to the power of heavy cutting and light cutting process.

Influence rules of design and operation parameters on energy consumption: In the energy consumption factor model as shown in Fig. 8, the energy form of P_{sp}, P_{sa}, P_{hf}, P_{hp}, P_{lf} and P_{lp} are all mechanical energy. Equation 11, 12 correspond to mechanical energy power of translational and rotational motion, respectively:

$$\begin{aligned} P &= F_i v_i \cos\theta_i \\ P &= M_j \omega_j \end{aligned} \tag{11}$$

Furthermore, P_{sn}, P_{sa}, P_{hf}, P_{hn}, P_{lf} and P_{ln} can be expressed as:

$$\begin{aligned} P_{sp} &= T_p \cdot \omega_s(t) \\ P_{sa} &= T_{sa} \cdot \omega_s(t) \\ P_{hf} &= T_{hf} \cdot \omega_h(t) \\ P_{hp} &= T_p \cdot \omega_h(t) \\ P_{lf} &= T_{lf} \cdot \omega_l(t) \\ P_{lp} &= T_p \cdot \omega_l(t) \end{aligned} \tag{12}$$

where, T_n denotes tightening torque caused by ball screw pre-tightening force, T_{sa} is accelerating torque of the feeding system, T_{hf} T_{lf} are, respectively cutting load torque (Nm) in the heavy cutting state and light cutting state, ω_s (t) ω_h (t) ω_l (t) (rad sec^{-1}), respectively correspond to the rotating speed of feeding system in the high-speed feeding state, heavy cutting state and light cutting state.

Combining theoretical derivation and design experience, the following relation can be obtained:

$$\begin{aligned} T_p &= \frac{F_p L_s}{2\pi} \cdot \frac{1-\eta^2}{\eta^2} \\ T_{sa} &= \left(J_m + \frac{\rho\pi d^4 L_g}{32} + \sum m_j \left(\frac{L_s}{2\pi}\right)^2\right) \cdot \frac{2\pi a}{L_s} \\ T_{hf} &= \frac{F_h L_s}{2\pi\eta} \\ T_{lf} &= \frac{F_l L_s}{2\pi\eta} \\ \omega_s(t) &= \frac{2\pi a t_a}{L_s}, 0 < t \le \frac{v_{max}}{60a}, -a_{max} \le a \le a_{max} \\ \omega_h(t) &= \frac{\pi v_h}{30 L_s} \\ \omega_l(t) &= \frac{\pi v_l}{30 L_s} \end{aligned} \tag{13}$$

where, d, d_2, respectively denote screw diameter (m) and screw thread bottom diameter (m), L_p, L_s, respectively correspond to length of the screw (m) and lead (m), ρ denotes density (kg m^{-3}) of screw material, η is ball screw pair efficiency, m_i is linear moving parts mass (kg), J_m is motor inertia (kg m^{-2}), F_h, F_l, respectively indicate cutting force (N) of heavy cutting state and light cutting state, F_n is ball screw pre-tightening force N, α, t_α, respectively correspond to feeding acceleration (m sec^{-2}) and acceleration time(s), v_h, v_l, respectively correspond to movement speed (m min^{-1}) of heavy cutting state and light cutting state, v_{max}, α_{max}, n_{max}, respectively correspond to maximum feeding speed (r min^{-1}), maximum feeding acceleration (m sec^{-2}) and the highest speed (r min^{-1}) of screw.

According to energy consumption factors as shown in Fig. 8 and the relational expression between design variables and energy consumption factors as shown in Eq. 12 and 13, the influence rules of design parameters, such as screw diameter d, lead P_h, rotational inertia of the motor J_M and worktable mass m_T on the energy consumption can be obtained, as shown in Fig. 9.

According to Fig. 9, the input power is directly proportional to screw diameter d, worktable mass m_T and motor rotating inertia J_M, it is inversely proportional to the lead P_h.

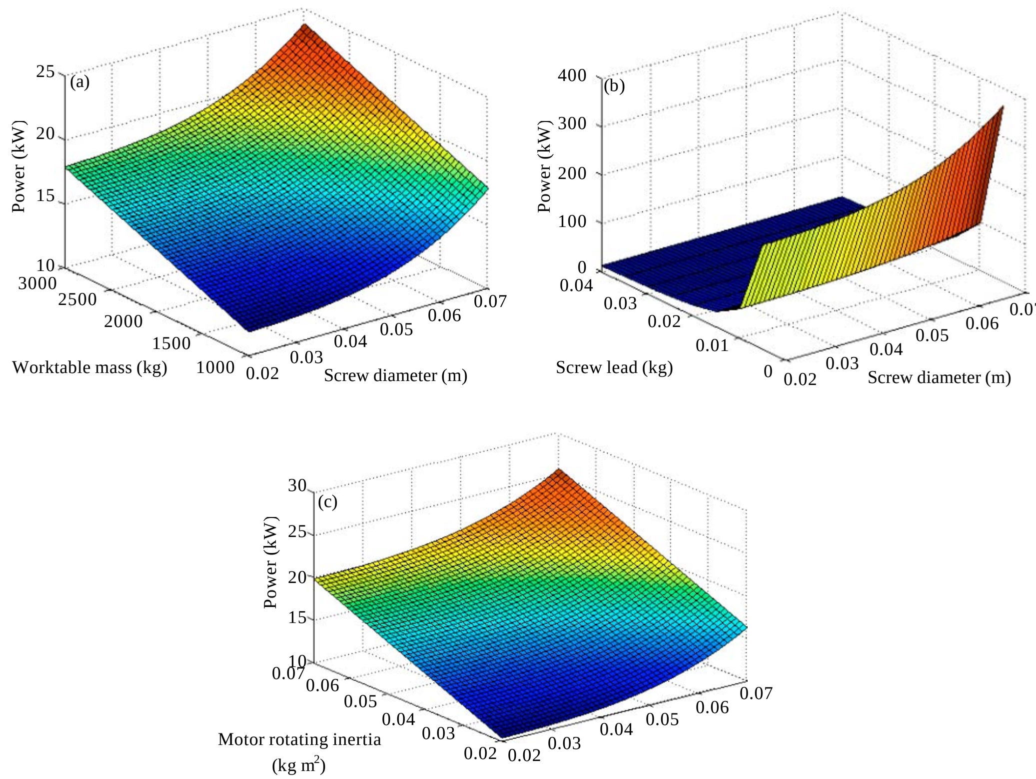

Fig. 9: Influence rules of design parameter on energy consumption, (a) Influence of m_T and d on input power, (b) Influence of d and P_h on input power, (c) Influence of d and J_M on input power

Table 3: Influence of working conditions on input power

High	Heavy	Light	P	High	Heavy	Light	P
0.1	0.1	0.8	5.88	0.5	0.1	0.4	26.37
0.1	0.3	0.6	5.86	0.5	0.3	0.2	26.35
0.1	0.5	0.4	5.84	0.5	0.5	0	26.33
0.3	0.1	0.6	16.12	0.7	0.1	0.2	36.61
0.3	0.3	0.4	16.11	0.7	0.3	0	36.59
0.3	0.5	0.2	16.09				

Different parts correspond to different process routes and cutting plans. Corresponding to Fig. 8, a, b and c% need selecting different values for different operation process, a+b+c% = 1. The influence of different operation conditions on energy consumption as shown in Table 3.

With the time proportion of high-speed feeding increases during the operation process, the energy consumption of Y-axis feeding system power increases gradually.

CONCLUSION

Considering the characteristics of large load-bearing, high speed, high precision and high energy consumption of Y-axis feeding system with vertical shifting worktable, the influence rules of design and operation parameters on natural frequency and energy consumption were analyzed and the following conclusions were obtained:

- The influence of worktable position on natural frequency of Y-axis feeding system is significant. When the worktable is in the middle of the screw, the natural frequency reaches the largest value, with worktable moving up and down, the natural frequency decreases gradually
- The natural frequency of Y-axis feeding system is inversely proportional to the mass of worktable and work piece and is directly proportional to screw diameter
- Energy consumption is related closely to design parameters, which is directly proportional to screw diameter, worktable mass and motor rotating inertia and inversely proportional to the lead
- The influence of operation states of feeding system on energy consumption is significant, energy consumption increases with the time proportion of high-speed feeding increases

The optimal design parameters can be determined further aiming at the goal of high- natural frequency and low energy consumption. And light weight and high strength also should be taken into consideration.

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