A Method of Chatter-Free Milling Parameters Optimization for Processing with High Energy Efficiency

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ABSTRACT: The goal of machining is to fulfill processing for high energy efficiency on the basis that processing quality is guaranteed. Chatter-free cutting is a necessary condition to guarantee processing quality. In order to improve the energy utilization rate of milling, a cutting parameters optimization method for milling is proposed with chatter-free cutting as a constraint and energy utilization rate as an optimization objective. First of all, energy consumption characteristics of machine tool are analyzed and high-speed milling & cutting parameters optimization model is established with high energy efficiency as a goal and chatter-free stable cutting as a constraint. Next, on the basis of energy consumption characteristics of machine tool, an optimization model for high-speed chatter-free milling & cutting parameters is established with high energy efficiency as a goal. Stable domain chart for cutting is used to determine optimization range of rotational speed of main shaft. Optimization range of cutting depth and width and feeding speed is determined in combination with cutting force, cutting power, cutting speed and other constraints. Optimized step length of parameters is selected properly so as to obtain cutting parameters rapidly. In the end, confirmatory experiment is performed on a 5-axis engraving and milling machine. Result of the experiment shows energy utilization rate is improved by 154.5%, total energy consumption reduced by 61.5% and processing time shorten by 74.8%.

1. INTRODUCTION
Numerically-controlled machine tools are widely used in modern machining workshop. Its characteristics of energy consumption are complicated, total energy consumption is high and energy efficiency is low. How to reduce energy consumption and improve energy efficiency of machine tools is an important research subject to implement green manufacturing. In the stage of machine tool design, the energy utilization rate can be improved through lightweight design. Method, procedure and specification of specific optimization design has been proposed in ISO14955; however, such method cannot further improve the energy efficiency of machine tools during use [1]. Hu Shaohua et al proposed rotational speed of main shaft might be selected properly so as to reduce the no-load power during use [2]. Cai Wei et al proposed concepts and corresponding implementation method of sub-divided energy consumption limit and multi-objective energy consumption baseline, providing an effective measure for energy consumption monitoring and management, and energy efficiency improvement for machine tools [3,4]. In terms of energy-saving study on machine tools fulfilled through cutting parameters optimization, Li Congbo et al [5] and Zhou Zhiheng et al [6] used an optimization model based on empirical mechanical model to optimize parameters of vehicle processing and milling respectively and fulfill low-carbon emission, but did not consider cutting stability condition. Li Kangju [7] proposed chatter during processing was effectively controlled by changing rotational speed and feeding speed of main shaft, but
did not consider energy optimization. Li Yao et al [8] considered cutting stability condition and used optimization model with carbon emission of milling as a goal to obtain high-energy chatter-free processing conditions; however, the calculation process was complicated.

In the process of present cutting parameters optimization, advanced algorithm is used to seek the optimal cutting parameters on the basis of empirical parameters or recommended value in relevant manual9]. Generally, in order to ensure no chatter during cutting, empirical value of cutting parameters or value of cutting parameters recommended in manual of machine tool (or cutter) is so conservative that processing capacity of numerically-controlled machine tool cannot be fully fulfilled [10]. However, if radical processing parameters are selected during processing, it is apt to occur cutting chatter, which may lead to severe consequences, broken cutter, unqualified processing quality and even damaged machine tool.

Thus, a parameters optimization method is proposed in this paper for processing at high energy efficiency where it is ensured that chatter will not occur. First of all, optimized parameters model is established with chatter-free cutting as a constraint and energy efficiency as an objective function. Next, range of parameters optimization for chatter-free cutting is determined in accordance with dynamic performance of machine tool-cutter, and optimized parameters are obtained by a simple algorithm. In the end, effectiveness of such method is verified by experiment.

2. PARAMETERS OPTIMIZATION MODEL FOR MILLING WITH HIGH ENERGY EFFICIENCY

2.1 Energy consumption characteristics of machine tool

In accordance with consumption characteristics of energy-consuming components of machine tool, energy consumption of machine tool can be roughly divided into 3 parts: energy consumption of cutting $E_{cut}$, varied energy consumption $E_{var}$ and fixed energy consumption $E_{cont}$ [11]. Energy consumption of cutting $E_{cut}$, used to remove energy consumed by excessive materials of workpiece, is integral of cutting power against time. Varied energy consumption $E_{var}$, which refers to energy consumption of machine tool drive system (including main shaft system and feeding system) during working, is integral of no-load power of drive system against time. Fixed energy consumption $E_{cont}$, which refers to energy consumption of auxiliary components (such as fan motor, servo and cooling pump) of machine tool during processing, is integral of power consumed by auxiliary components against time. Specific relation among them can be expressed as follows,

$$P_{in} = P_{cut} + P_{var} + P_{cont}$$
$$E_{in} = \int P_{cut dt} + P_{var dt} + P_{cont dt}$$
$$E_{cut} = \int P_{cut dt}$$
$$E_{var} = \int P_{var dt}$$
$$E_{cont} = \int P_{cont dt}$$
$$U = E_{cut}/E_{in}$$

(1)

In the equations, $P_{in}$ is total input power of machine tool; $P_{cut}$ is cutting power; $P_{var}$ is no-load power of machine tool drive system; $P_{cont}$ is power of auxiliary system of machine tool; $E_{in}$ is total energy consumption of machine tool; $E_{cut}$ is energy consumption of cutting of machine tool; $E_{var}$ is varied energy consumption; $E_{cont}$ is fixed energy consumption; $U$ is energy utilization rate (namely percentage of energy consumption of cutting in total energy consumption).

(1) Estimation of no-load power $P_{var}$ of machine tool drive system. Since no-load power of feeding system is small (only tens of watts, accounting for about 1% of total power of machine tool) and negligible, only no-load power of main drive of machine tool is considered in machine tool drive system. Hu Shaohua et al [12] indicated most main drive systems of modern machine tool control main shaft system by means of variable voltage and variable frequency.

(2) Power $P_{cont}$ of auxiliary system of machine tool is a constant. Power of auxiliary system (such as fan motor, servo and cooling pump) is a constant generally without relation to processing state.
(3) Cutting power $P_{cut}$. As known from literature [13], cutting power of machine tool is in direct proportion to material removal rate

$$P_{cut} = K \cdot MRR$$  \hspace{0.5cm} (2)$$

In the equation (2), $K$ is a coefficient of material removal rate (related to hardness and mechanical properties of materials), $J/m^3$; $MRR$ is material removal rate, $mm^3/min$.

(4) No-load power of drive system $P_{m_n}$ and power of auxiliary system $P_{aux}$ are combined as no-load power $P_u$ of machine tool. When rotational speed of main shaft of machine tool is designated, both no-load power of drive system $P_{m_n}$ and power of auxiliary system $P_{aux}$ are constants. Thus, no-load power of drive system and power of auxiliary system are combined and called no-load power $P_u$ of machine tool, which can be fitted with equation (3)

$$P_u(n) = \begin{cases} 
A_i n^2 + B_i n + C_i & f \leq 50 \text{ Hz} \\
A_i n^2 + B_i n + C_i & f > 50 \text{ Hz} 
\end{cases}$$  \hspace{0.5cm} (3)$$

In the equation, $P_u$ is no-load power of machine tool; $A_i, A_1, B_i, B_1, C_i$ and $C_i$ are fitting coefficients.

Then equation (1) can be simplified as

$$\begin{align*}
E_U &= E_{cut} + E_u \\
U &= E_{cut} / E_u
\end{align*}$$  \hspace{0.5cm} (4)$$

2.2 Processing stability requirements

During milling, chatter will occur in unreasonable or excessively radical cutting parameters. Chatter refers to intensive self-excited vibration which occurs in the cutting process. It originates from the cutting force and the vibration coupling between cutter and workpiece and belongs to a typical unstable cutting state. Chatter will directly influence quality of finished surface of workpiece, shorten service life of machine tool and tool, and even damage functional components of machine tool. In production practice, parameters recommended by cutter producer and machine tool manufacturer and empirical values of processing personnel are used generally to select cutting parameters. In most cases, conservative parameters are selected, which is detrimental to total energy utilization rate and production efficiency. It is also one of main reasons why energy utilization rate is extremely low in the machining industry. According to cutting stability theory [14] proposed by Altinas, provided that rotational speed and cutting depth meet equation (5), stable cutting requirements will be obtained.

$$\begin{align*}
\lim_{pa} &= \frac{2\pi A_i (1 + \kappa^2)}{zK} \\
\tan \frac{\pi}{2} &= \frac{2k_i + 1}{\pi - 2\tan \kappa} \\
n &= \frac{60\omega_k}{2k_i + 1 + \pi - 2\arctan \kappa}
\end{align*}$$  \hspace{0.5cm} (5)$$

In the equation, $a_{p_{lim}}$ is extreme cutting depth in chatter; $K_i$ is coefficient of tangential cutting force; $z$ is number of milling cutter teeth; $\kappa = \Lambda_i / \Lambda_p = \sin(\omega T)/(1 - \cos \omega T)$; $\Lambda_i$ and $\Lambda_p$ are imaginary part and real part of eigenvalue of processing system characteristics equation; $\omega_k$ is chattering frequency; $T$ is cutting period and $k_i$ is integer of ripple left from arc cutting. To ensure stable cutting, a certain margin is kept, namely $a_p \leq \lambda \cdot a_{p_{lim}} (\lambda \leq 0.9)$.

2.3 Other constraints

(1) Constraint for rotational speed of main shaft (namely, constraint for cutting speed). Numerically-controlled machine tools are provided with definite rotational speed of main shaft, cutting parameters shall be selected in a way that meets constraint for rotational speed of main shaft, and allowed cutting speed of cutter meets the equation (6).
In the equation, $d_c$ is diameter of milling cutter; $v_r$ is cutting speed; $n_{min}$ and $n_{max}$ are minimum and maximum of rotational speed of main shaft; $V_{min}$ and $V_{max}$ are minimum and maximum of allowed cutting speed of cutter.

(2) Constraint for cutting force (constraint for cutting torque). During milling, cutting force $F_z$ of shafts cannot exceed feeding resistance of shafts of machine tool. Maximum feeding resistance $F_{max}$ can be obtained by checking machine tool manual.

$$F_z \leq F_{max}$$

(3) Power constraint. Cutting power cannot exceed the maximum power of main shaft. The maximum power of main shaft of machine tool can be obtained by electrical nameplate data of main shaft or machine tool manual. $\eta$ is efficiency of main shaft motor and $P_{eNc}$ is rated power of motor.

$$P_{eNc} \leq \eta P_{eN}$$

(4) Feed constraint. Feed is required to be between maximum feed and minimum feed of machine tool.

$$f_{min} \leq f \leq f_{max}$$

2.4 Optimization model considering energy consumption characteristics and cutting stability

Energy utilization rate is a complicated function which covers efficiency (processing time), energy consumption (energy consumption of cutting and total energy consumption), relevant parameters (rotational speed of main shaft, cutting width and cutting speed), and other variables. Thus, it is an issue of typical multi-constraint and multi-optimization objective in terms of high-speed milling parameters optimization indexes. Its mathematical model is as follows:

$$\max \{U = \frac{P_{eNc}}{P_{eNc} + F_z} \}$$

s.t.

$$a_z \leq \frac{d_c}{2} \leq a_{zhc}$$

$$\min \left( \frac{\pi n_{min}}{1000}, V_{min} \right) \leq v_r \leq \max \left( \frac{\pi n_{max}}{1000}, V_{max} \right)$$

$$F_z \leq F_{max}$$

$$P_{eNc} \leq \eta P_{eN}$$

$$f_{min} \leq f \leq f_{max}$$

3. OPTIMIZATION STRATEGY

As mentioned above, high-speed milling parameters optimization for energy saving is a matter of parameters optimization under typical constraints. Milling process is constrained by nonlinear conditions, such as cutting force, power, cutting speed and chatter stability. At present, when stability requirements are not considered, for cutting parameters, particle swarm algorithm, tabu algorithm or other method is generally used for solution with a large calculated quantity and a low solution speed [5,15]. If stability requirements are considered, the calculation will be more complicated and last for a longer time. Thus, it is necessary to propose a rapid solution algorithm suitable for engineering application. A rapid solution algorithm for cutting parameters based on Cutting Stability Chart is proposed in this paper. The key procedures are described as follows:

A. In accordance with stable domain equation (equation 6), Stable Domain Diagram can be obtained as shown in Fig.1, and it can be seen that stable cutting zone is below the curve and cutting chatter zone is above the curve. Range of rotational speed of main shaft can be determined accordingly. Generally, the widest lobe zone of two stable domains is selected as range of parameters optimization, and rotational speed corresponding to the highest point of curve is the optimal central value of rotational speed of main shaft, namely
B. Optimization range of radial cutting depth $a_e$ : During coarse processing, $a_e \in [0.5 \cdot D, 0.9 \cdot D]$ ($D$ is diameter of cutter); during fine processing, $a_e = 0.1 \cdot D$ or $a_e = \xi$ ($\xi$ is processing margin and meets $\xi \leq 0.1 \cdot D$)

C. Optimization range of axial cutting depth $a_p$ : $a_p \leq \lambda \cdot a_{plan} |j| \lambda \leq 0.9$, where $a_{plan}|j|$ stands for maximum depth at level $i$ of rotational speed and level $j$ of cutting depth and is determined by the stable domain equation (equation 6).

4. OPTIMIZATION CASE

4.1 Experimental facilities and processing task
Milling plane of Beijing Jingdiao CNC500 is studied in this experiment, and specific parameters of machine tool, cutter and workpiece are the same as that in literature [5].

4.2 Optimization results and analysis
As analyzed by Cutting Stability Chart of Machine Tool, speed of chatter-free main shaft $n$ is between 4500rpm and 5500rpm and between 8000rpm and 10000rpm. Maximum cutting depth is $a_e = 3.6\text{mm}$ and $n = 9000\text{rpm}$ respectively. Optimized cutting parameter with energy consumption rate as a goal is $(n, a_e, a_p, v_j) = (9000, 2.0, 7.5, 600)$. As a result, processing efficiency and energy utilization rate are reduced. In comparison with experiment-based optimization results in literature [5], total energy consumption $E_n$ is reduced to 32.2%; in comparison with optimization results in literature [5] where $E_n$ serves as an optimization objective, total energy consumption $E_n$ is reduced to 38.5%, cutting time $T$ is reduced to 25.2%, energy utilization rate $U$ is increased to 254.5%. Meanwhile, each tooth cutting $f_j$ is reduced to 76.6% while feeding speed is increased to 157.7%.

5. CONCLUSION
Stable domain of high-speed milling is established by means of dynamic characteristics of machine tool-cutter in this paper. Then optimization range of rotational speed of main shaft, cutting width and cutting depth is selected reasonably for stable domain of high-speed milling. And milling parameters are optimized by a simple iteration algorithm so as to fulfill efficient energy-saving milling. Effectiveness of such method is verified by experiment results and has the following advantages: (1) Milling parameters are optimized under constraint of stability requirements; conservativeness is that cutting parameters are selected in accordance with conventional experiment to a large extent; (2) Range of parameters optimization is selected in stable domain, which has prevented blind searching for cutting parameters and reduced optimization process and calculated quantity.
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