

Effects of servo system on limited cutting width in CNC heavy cutting

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Abstract: A mathematical model of the computer numerical control (CNC) heavy cutting servo system including chatter in cutting courses was constructed for the chatter in CNC heavy cutting. The theoretical analysis, computer simulation and orthogonal tests on this model show that increasing the gain of position K_{pp} can improve the rapid tracking performance of machine tools, and decreasing the delay time of speed loop τ_s can quickly eliminate the static error in the system, but the limited cutting width b_{lim} will descend correspondingly; excessively large or excessively small gain of speed loop K_{ps} can result in decreasing b_{lim} ; optimizing K_{pp} , τ_s and K_{ps} can improve the dynamic and static performance of the system and increase b_{lim} . It is easy and feasible to optimize the servo parameters by the orthogonal test. This method can effectively improve the system's stability and limited cutting width and it is suitable for the CNC heavy cutting of heavy-duty machine tools.

Key words: chatter; computer numerical control heavy cutting; simulation; orthogonal test

The computer numerical control(CNC) for heavy cutting is mainly used in the heavy-duty CNC machine tools owned by metallurgic plants, mine plants, and engineering machine plants etc. for rough machining or semi finishing of large size workpieces. The cutting speed cannot be too high when large size workpieces are worked on with the heavy-duty CNC machine tools. Optimizing the cutting width and depth is the main method to improve the productive efficiency^[1]. So studying how to increase limited cutting width in the CNC heavy cutting is one of the important methods to improve the working efficiency and accuracy of heavy-duty CNC machine tools and the product quality.

There are many methods to calculate the limited cutting width of machine tools, such as the analytical method, the graphical method, the algebraic criterion method and the simulation method, which determine the steady critical point of the system by the distributing regularity of the system's latent root, and then the value of the limited cutting width can be obtained. In the past, study on the limited width was mainly focused on theoretical analysis and application of mechanical systems, but it was very difficult to manipulate.

For CNC heavy cutting, the chatter system is an inner subsystem encompassed in the entire closed-loop servo system. The factors affecting cutting stability include not only mechanical structure parameters, cutting amounts and the parameters of the cutting process, but also control mode and three-loop adjusting parameters. Because of adding the regenerated chatter subsystem, the zero-pole points distributing condition of the CNC heavy cutting servo system is changed. This change may worsen the stability of the cutting system. Optimizing the regulator's parameters for each loop can rearrange the zero-pole distributing condition. Consequently, the stability of the cutting system is improved. Many measures that avoid the cutting chatter in general machine tools either affect the working efficiency (such as decreasing the cutting parameters) or are difficult to implement (such as cutting with variable speed and active controls etc.)^[2]. Compared with the above measures, the method for obtaining the largest cutting width by adjusting the regulator's parameters for the servo system not only is easy to use, but also can improve the cutting efficiency^[3].

1 Modeling and Analyzing of CNC Heavy Cutting Servo System

1.1 Establishing mathematical model

For an actual CNC heavy cutting machine tool, the drive mechanism and servo driving system are not two in-

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the open-loop transfer function of the entire servo system encompassing the cutting loop can be transformed into

$$G(s) = \frac{K_{pp} K_{ps} K_{pi} \left(\frac{1 + \tau_s}{\tau_s} \right)}{\frac{s W_{ASR} W_{ACR}}{K_{bs} G_c(s)} + G_1(s) G_2(s) W_{ASR} W_{ACR} + \frac{K_t s (T_v s + 1) (T_i s + 1) (T_{PWM} s + 1)}{K_{bs} G_c(s)}} \quad (2)$$

According to the auto control theory, the gain of the open loop has an important effect on the system's character, such as quick response capability and stability. The gain of the cutting system's open-loop transfer function described in Eq. (2) is $K_{pp} K_{ps} K_{pi} / \tau_s$. This value is not only relevant to the three-loop's gains of the servo system, but also relevant to the integral action time of the speed loop. It shows that adjusting the above parameters can change the gain of the forwarding channel, and as a result the dynamic and static character of the system and the stability of machine tools is also changed.

2 Simulation and Analysis of Servo Parameters' Effect on Limited Cutting Width

The adjusting form of P-PI is adopted commonly in modern AC servo systems, namely, a P regulator is adopted in the position loop and a PI regulator is adopted in the speed loop. As far as the current loop is concerned, the P regulator is adopted and needs no adjusting. For example, the current loop's gain of the PANASONIC servo system is determined by the machine model, and the user cannot adjust it; another example is that the current loop's gain of the SIEMENS driver system can be obtained by calculation, and needs no optimization. So in the following simulation, the open loop system's root locus is drawn with the variables K_{pp} , K_{ps} and τ_s , where K_{pp} is the gain of the position loop, K_{ps} is the gain of speed loop and τ_s is the integral action time of the speed loop.

According to Ref. [3], the simulation parameters are selected as follows: $T_v = 10$ ms, $T_i = 2$ ms, $T_{PWM} = 1.67$ ms, $R_a = 0.24$ Ω , $L_a = 2.5$ mH, $K_t = 2.7$ N·m/A, $J = 0.059$ kg·m², $K_{bs} = 16$ mm, $M = 3\,000$ kg, $C = 3\,000$ kg/s, $K = 28$ MPa, $K_c = 75$ MPa, $\tau = 0.4$ s, $b = 12$ mm. The regenerated feedback time-lag function relevant to spindle's speed is expanded as the fourth-order Pade function which can be expressed as Eq. (3) and insert Eq. (3) in Fig. 1. The figures of root locus are drawn by Matlab, which are illustrated in Fig. 2.

$$e^{-\tau s} = \frac{1 + \sum_{k=0}^N \frac{(-\tau s)^k}{k!}}{1 + \sum_{k=0}^N \frac{(\tau s)^k}{k!}} = \frac{a_1 s^4 + b_1 s^3 + c_1 s^2 + d_1 s + e_1}{a_2 s^4 + b_2 s^3 + c_2 s^2 + d_2 s + e_2} \quad (3)$$

Fig. 2(a) shows the variable regularity of the root locus with variable K_{pp} (at this moment, $K_{ps} = 7.5$ and $\tau_s = 40$ ms). This figure shows that when K_{pp} is small, all the roots of the system are located in the negative plane of the complex plane and the system is stable; with the increase of K_{pp} , a pair of root loci move to the positive plane of the complex plane gradually, and when K_{pp} increases to 2 300, root locus branch intersects the imaginary axis. The system loses stability as a result.

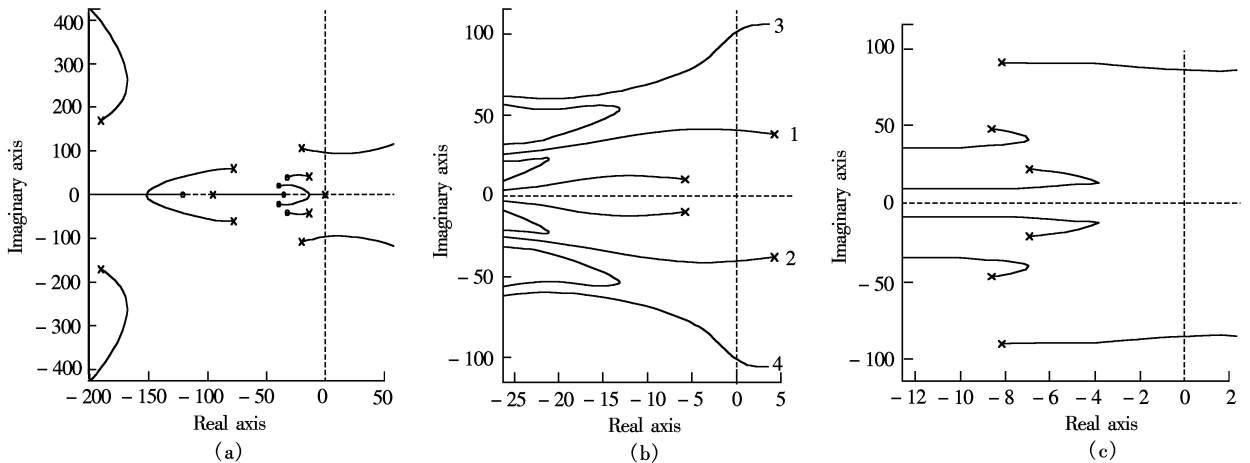


Fig. 2 Root locus with variable parameters. (a) K_{pp} ; (b) K_{ps} ; (c) τ_s

When $K_{pp} = 2\,000$ and $\tau_s = 40$ ms, the root locus of the open-loop system illustrated in Fig. 2(b) can be obtained by varying K_{ps} . Fig. 2(b) shows that when K_{ps} is small (about 2), the branch of a pair of root loci (curves 1 and 2) locate in the positive plane, then the system is not stable. With the increase of K_{ps} , all the roots are located in the negative plane, then the system is stable; but when K_{ps} increases further (to about 12), a branch of another pair of root loci begins to locate in the positive plane (curves 3 and 4), so the system loses stability again as a result.

The root locus of an open-loop system with variable parameter τ_s is illustrated in Fig. 2(c) (at this moment, $K_{pp} = 2\,000$, $K_{ps} = 7.5$). When τ_s is large, the integral action of the PI regulator is small, then the system is stable; with the decreasing of τ_s , the integral action becomes larger and the stability margin decreases; when $\tau_s = 30$ ms, a pair of root loci move to the positive plane and the system loses stability as a result.

3 Analysis of Experiment

The experiment is done in the large-scale CNC trace-milling machine remade by the authors. The main structure and parameters of the machine tool are shown as follows: the CNC system is C2 of FIDIA, the servo driving systems are 611UE and 1FT5134 of SIEMENS, $M = 3\,500$ kg, $d = 80$ mm, $K_{bs} = 16$ mm, $l = 3$ km. Let the limited cutting width of the system be b_{min} and the response delay of the ramp function be τ .

In order to decrease the experimental times and obtain effective experimental results, orthogonal test and single factor experiments are made on the three main parameters K_{pp} , K_{ps} and τ_s in this paper, respectively.

3.1 Orthogonal test

According to the engineering-debugging experience, the orthogonal test is made in terms of a three-factor and four-horizontal orthogonal table $L_{16}(4^5)$. The experimental factors and levels are illustrated in Tab. 1.

The performance index of the servo system includes stability, rapidity and accuracy, which is a multi-index system. So in the orthogonal test, the synthesised point system can be selected to evaluate each index of every experiment and, letting the synthesised marks be the total index of experiment, then the multi-experimental index is transformed into a single experimental index. Subsequently, the method of single-index experimental direct-vision analysis is applied to analyze it. According to the characteristics and the performance requirements of the CNC heavy cutting servo system, stability and rapidity are selected as indices^[7]. Meanwhile, considering the difference of the two indices' effect on the performance of the servo system, the formulation of a synthesised point system can be obtained, and in terms of the calculation the importance of stability is four times that of rapidity. The formulation can be expressed as

synthesised mark = 4 × limited cutting width – response delay of ramp function

The results of the orthogonal test are illustrated in Tab. 2. The range shows that the primary and secondary relation of factors is B—C—A, that is, the main factors effecting on the cutting width of the machine tool and the rapidity of the servo system are the gain of the speed loop, the integral action time of the speed loop and the gain of the position loop in turn. The analysis accords with the regularity of actual engineering debugging, namely, when the performance of a servo system is optimized, the gain of the speed loop and the integral action time are optimized firstly, then the gain of the position loop is optimized again (such as for the CNC system of SIEMENS).

Tab. 1 Factors and levels of orthogonal test

Level	K_{pp}	K_{ps}	τ_s/ms
1	1 500	3	30
2	1 700	5	40
3	1 900	7	50
4	2 150	10	70

Tab. 2 Orthogonal test and analysis

Number	A	B	C	b_{lim}/mm	τ/ms	Synthesised mark
1	1	1	1	7	72	−44
2	1	2	2	35	103	37
3	1	3	3	28	90	22
4	1	4	4	20	87	−7
5	2	1	2	11	68	−24
6	2	2	1	13	67.7	−15.7
7	2	3	4	37	104	44
8	2	4	3	18	67.4	4.6
9	3	1	4	20	82	−2
10	3	2	3	32	86	42
11	3	3	2	20	62.5	17.5
12	3	4	1	1	50	−46
13	4	1	2	5	45	−25
14	4	2	1	5.5	44	−22
15	4	3	4	29	72	44
16	4	4	3	16	51.5	12.5
K_1	8	−95	−127.7			
K_2	8.9	41.3	5.5			
K_3	11.5	127.5	81.1			
K_4	9.5	−35.9	79			
R	3.5	222.5	208.8			

On the other hand, according to the value of K in each line, the optimal horizontal combination is A3B3C3, namely, the gain of position loop and speed loop are equal to 1 900 and 7, respectively. The integral action time of speed loop is equal to 50 ms.

3.2 Experiment of single factor

Every factor's effect on the dynamic characteristics of a CNC heavy cutting system can be obtained by the experiment of a single factor, meanwhile, the simulation results in the last section can be verified. Tab. 3 to Tab. 5 show the experimental results of the effect on the performance of machine tools by the gain of the position loop, the gain of the speed loop and the integral action time of the speed loop, respectively^[8].

3.2.1 Effect of K_{pp} on the performance of servo system

The experimental results in Tab. 3 show that the CNC heavy cutting servo system with a smaller K_{pp} has a larger stability margin, and the machine tool can obtain a larger b_{lim} , but the dynamic adjusting time is longer, which results in larger tracking error, especially when several axes interpolate a complicated curved face, the profile tracking error is obvious; with the increase of K_{pp} , the response speed of the system becomes rapid, but the stability becomes worse and the limited cutting width of the machine tool descends quickly. The above regularity accords with the analysis of root locus illustrated in Fig. 2(a). In the process of actual debugging, the machine tool's dynamic and static performance can be optimized further by a feed forward loop^[9]. The feed forward loop makes the system have good rapid tracking performance in the circumstance of small gains of the position loop, then the contradiction between the stability and rapidity can be solved effectively.

Tab. 3 Effect of K_{pp} on b_{lim}

K_{pp}	K_{ps}	τ_s/ms	b_{lim}/mm	τ/ms
1 500	7.5	40	23	67
1 700	7.5	40	19	59
1 900	7.5	40	16	53
2 000	7.5	40	13	50
2 150	7.5	40	10	47

3.2.2 Effect of K_{ps} on the performance of servo system

Tab. 4 shows the relation between K_{ps} and b_{lim} and rapid response characteristics. When K_{ps} is smaller, the branches of a pair of root loci (curves 1 and 2) illustrated in Fig. 2(b) are close to the positive plane of the complex plane, the stability of the system is bad, and the corresponding b_{lim} in Tab. 4 is smaller. After increasing K_{ps} , the root locus of the system moves to the negative plane and the actual b_{lim} increases consequently. Increasing K_{ps} further, a pair of root loci (curves 3 and 4) begin to approach to the positive plane, the stability of system becomes worse again, and the actual b_{lim} of machine tool descends correspondingly. Tab. 4 also shows that the variety of K_{ps} has a little effect on the rapid response characteristic of the system. The experimental and the simulation results show that too large or too small K_{ps} results in loss of stability, so in the process of actual engineering debugging, the optimal K_{ps} can be sought for by optimizing (hand or automated), which makes the machine tool obtain a b_{lim} as large as possible.

Tab. 4 Effect of K_{ps} on b_{lim}

K_{pp}	K_{ps}	τ_s/ms	b_{lim}/mm	τ/ms
2 000	3	40	6	49.5
2 000	4	40	14	50.5
2 000	5	40	17	49.0
2 000	6	40	16	49.5
2 000	7	40	14	50.0
2 000	8	40	12	50.5
2 000	9	40	7	49.5
2 000	10	40	6	51.0

3.2.3 Effect of τ_s on the performance of servo system

Tab. 5 shows the effects of τ_s on b_{lim} and rapid response characteristics. The data in this table indicates that a larger b_{lim} can be obtained by adopting a larger integration time constant; and b_{lim} descends quickly when decreasing integral action time. According to Fig. 2(c), after decreasing integral action time, a branch of a pair of root loci will approach to the positive plane of complex plane, and the stability descends as a result. As for K_{ps} , variance of this parameter influences the rapid response characteristics of the system a little. In the process of engineering debugging, considering the requirements of b_{lim} , dynamic and static performance comprehensively, integral action time should be selected as small as possible, which makes the servo system decrease in static error quickly.

Tab. 5 Effect of τ_s on b_{lim}

K_{pp}	K_{ps}	τ_s/ms	b_{lim}/mm	τ/ms
2 000	4	70	21	51.0
2 000	4	60	21	50.6
2 000	4	55	20	50.5
2 000	4	50	18	50.5
2 000	4	45	16	50.5
2 000	4	40	14	50.5
2 000	4	35	8	50.5
2 000	4	30	1	49.5

4 Conclusions

1) A mathematical model of CNC heavy cutting servo feed systems is constructed which encompasses the dynamic cutting process. It shows that the servo system of CNC heavy cutting machine tools has important effects

on the limited cutting width of machine tools according to theoretical analysis and experiments. Increasing K_{pp} can improve the rapid tracking performance of a machine tool, but b_{lim} of the machine tool descends consequently; too large or too small a K_{ps} can result in decreasing b_{lim} of the machine tool, so it should be selected reasonably in debugging; small τ_s can eliminate the static error of the system quickly, but results in b_{lim} descending in the machine tool.

2) The adjustment method for optimizing the regulator's parameters on the servo system by the design of orthogonal tests is put forward. This method improves the efficiency of engineering debugging effectively and obtains good effects when applied in the CNC heavy vertical lathe and the CNC trace gantry type boring and milling machine tool.

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数控强力切削中伺服系统对极限切削宽度影响的研究

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摘要:针对数控强力切削中颤振问题,建立了包含切削过程颤振环节的数控强力切削伺服系统数学模型.对模型的理论分析、计算机仿真及正交试验验证表明:增大位置环增益 K_{pp} 可提高机床快速跟踪性能,减小速度环积分时间常数 τ_s 能迅速消除系统静差,但极限切削宽度 b_{lim} 会随之而下降;过大或过小的速度环增益 K_{ps} 都会导致 b_{lim} 下降;优化调节伺服系统 K_{pp} , τ_s 和 K_{ps} 可提高系统的动、静态特性及 b_{lim} . 正交实验优化伺服系统参数方法简单可行,能有效地提高切削系统稳定性和极限切削宽度,适用于重型机床的数控强力切削.

关键词:颤振;数控强力切削;仿真;正交试验

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