



Use of response surface methodology to optimal-parameters adjustment for CNC machine tool by corner speed control

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ABSTRACT

This paper mainly focuses on investigating the parameter adjustment of corner acceleration and deceleration speed, which mainly affects machining accuracy and efficiency, for CNC machine tool, coordinated with Regression Analysis Method and Taguchi Analysis Method to conduct the optimal design and prediction of the controller parameters. The equipment used in this study is FANUC high-end controller, its data acquisition software is servo guide. This study conducted analysis and adjustment for servo parameters of feed shaft on CNC accuracy machinery in three phases. In the first phase, Regression Analysis Method was adopted to conduct parameter screening from captured data; in the second phase, Regression Analysis Method and Taguchi Analysis Method were adopted to conduct the works of parameter optimization; and in the third phase, used both methods to carry out circular measurements and the planning and selection of important parameter data. In this study, Regression Analysis Method was used to predict the experimental data analysis, semi-normal probability chart, Plato and analysis of variance (ANOVA) were used to understand significant factors of parameters and effects of interactions, then calculated best value based on response surface chart and contour chart, and adopted Taguchi Analysis Method to conduct analysis, comparison and verification. The experimental result proved that the experiment after changed can improve experiment with verification, so the problem in parameter screening of Taguchi Analysis Method can be voided. This study adopted Experimental of Design (DOE) to carry out processing accuracy and processing efficiency.

Keywords: CNC controller; parameter adjustment; design of experiment

INTRODUCTION

Along with the advance of technology age, machine tools have become very important in automated production. The volume processing and manufacturing capacities as well as high-accuracy processing are unattainable by human. Machine tools are very popularly used in domestic and foreign factories, however, in the adjustment of controller parameters, usually only the Try Error Method is adopted to repeatedly adjust controller parameters, and no further way to break through. Therefore, the adjustment of controller parameters is a very important issue in factories using machine tools. Moreover, the controller is the core component of a machine tool, parts and components can not have high-accuracy if the parameters of controller have not been approximately adjusted and calibrated, so the controller in a machine tool really plays a very important role.

Explained that high-speed cutting can increase productivity, and lowered cutting force can reduce thermal deformation to allow fine roughness on surface and achieve more stability while cutting[1][2], Targeted on the planning of high-speed servo control feed rate and used servo loop control method to shorten processing time and reduce path error[3], Mentioned that the two major control loops used in machine tool systems are speed control loop and position control loop[4], they are used to control feed shaft and speed feedback, Interpolation technology

high-speed processing algorithm, made the original controller to increase processing speed[5], but in the course of high-speed processing of machine tool, the machine will inevitably produce vibration and cause accuracy error of processing, Compared a variety of acceleration and deceleration method and interpolation method, and proposed a new rule for poor accuracy while in interpolating[6], i.e., applying acceleration and deceleration control in interpolator to make processing more smooth to achieve high-accuracy effect. The well-known controllers used in domestic and foreign tool machine factories include such as FANUC, SIEMENS, MITSUBISHI, HEIDENHAIN, etc. In terms of the market share, for the controller used in major brands of tool machine factories, FANUC is still ahead of the pack among these four well-known brands, and it enjoys a very high utilization rate in domestic machine tool factories. In a study of using the features of 18i-MB controller to do parameter adjustment, it revealed that the functionality of FANUC 18i-MB controller can also achieve high-speed and high-accuracy processing [7].

2. Parameters affecting trajectory accuracy:

Reasons for errors generated while a CNC machine tool is accelerating and decelerating in the corner are many. As shown in Figure 1, while moving along two axes, P1, P2, and P3 are movement paths, corner error would be generated in the path of movement, the generated corner error started from point A to point B and C, and forms a triangle, this ABC contains all the errors, the error relationship (ε) between paths in ABC can be obtained from formula 2-17, while (ε_{\max}) is the maximum value of the corner error.

$$\varepsilon = \frac{\sqrt{2-2\cos\theta}}{\sin\theta} \cdot \varepsilon_{\max} \quad (1)$$

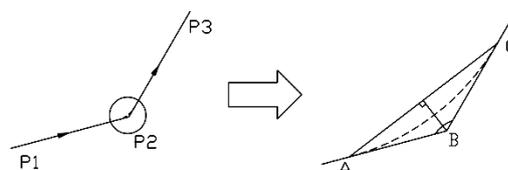


Figure 1. Schematic diagram of corner error

Use calculated corner error of automatic corner deceleration at corner speed and angle of cutting tool, feed rate automatically covers corners at both ends, as shown in Figure 2, there are four types of interior angles, including linear and circular movements between straight-line movements (tangent line of straight-line movement and circular movement between angles), and circular movement (between tangent lines of angle and circular movement). when identified as the inside part of the corner, set ratio for feed rate at between within the range of from the intersection point of the corner to L_e of previous program segment and within the range of from the intersection point of the corner to L_s of next program segment, distances L_e , L_s represent the straight-line distances between the points on center path of the cutting tool to the intersection point of the corner.

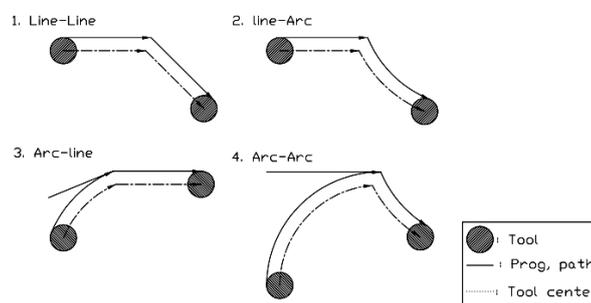


Figure 2. Schematic diagram of interior angle error

4. Laboratory equipment and experimental design:

4.1 Laboratory equipment

The laboratory equipment mainly includes Takumi's H10 gantry high-speed machine tool, and the controller model FANUC 18i-MB. The experimental setup is as shown in Figure 4.



Figure. 4 The actual experimental machine: the H10 high-speed machine tool

4.2 Experimental design

In the first phase of the main course in this study, conducted the process of high frequency filtering, mainly to reduce the effect of high frequency response on machine accuracy; the second phase is experimental parameters screening and analysis, main purpose is to analyze effect proportions of CNC controller parameters for corner acceleration and deceleration on accuracy; the third phase is testing and analysis, mainly to conduct optimization experiment for parameters with larger effect proportions, and compare and discuss the experimental result with the result of Taguchi Analysis Method.

In the experiment, planned experimental parameters for corner acceleration and deceleration measurements, mainly referenced recommended values provided by controller manufacturer, and conducted parameter screening experiment. The main parameters are listed in Table 2, including acceleration / deceleration time constant after cutting feed interpolation (1768), speed gain (2021), feed-forward coefficient (2092), and fine finishing acceleration / deceleration time constant (2109). Adjusted the parameter values affecting one fourth of corner acceleration and deceleration to perform one fourth corner acceleration and deceleration measurements, its moving direction is clockwise rotation, feed rate is 2000m/min, a rectangle with side length 20mm, and arc angle R5. After executed the measurement program, the result showed that all the vibrations generated while in high-speed cutting are very obvious on the convexes and overcuts of one fourth corner acceleration and deceleration, and all of these convexes and overcuts would have a very big effect on surface roughness and contour of workpieces while in high-speed cutting.

Table 2. Parameter addresses affecting circular measurements

Function Parameter	Backlash compensation		Position gain		Speed gain		Backlash accelerating rate	
	Parameter code	1768	2021		2092		2109	
Machine tool	X-axis	Y-axis	X-axis	Y-axis	X-axis	Y-axis	X-axis	Y-axis
original parameter settings	24		300		9900		0	
Changed parameter settings	16		300		9950		24	

A. Analysis of Variance (ANOVA)

The analysis method, used to simultaneously test whether the means of k populations are equal under the same significance level α , is called Analysis of Variance (ANOVA). Table 1 is the analysis of variance table [15].

ANOVA steps:

B. Test coefficient R^2

Model appropriateness can be determined by the determinant coefficient R^2 , and is defined as:

$$R^2 = \frac{SS_R}{SS_T} \quad (2)$$

SS_R is Regression Sum of Square, also called variance between populations:

$$SS_R = \sum_{i=1}^k \sum_{j=1}^{n_i} (y_i - \bar{y} \dots)^2 = \sum_{j=1}^{n_i} (y_i - \bar{y} \dots)^2 \quad (3)$$

SS_T is Total Sum of Square, also called total variance:

$$SS_T = \sum_{i=1}^k \sum_{j=1}^{n_i} (y_{ij} - \bar{y} \dots)^2 \quad (4)$$

$$SST = SSR + SSE$$

SS_E is Residual Sum of Square, also called variance within population:

$$SS_E = \sum_{i=1}^k \left[\sum_{j=1}^{n_i} (y_{ij} - \bar{y} \dots)^2 \right] \quad (5)$$

R^2 value is the ratio used to describe the variance between populations to experimental total variance value, i.e., the ratio can be described for total variance value of experimental data.

C. F-value or t-value test:

If want to detect whether the regression coefficient of an experimental factor is significant, can use F-value or t-value to perform statistical detection. MS_E is sum of residual squares, while MS_R is sum of average squares.

$$F = \frac{MS_R}{MS_E} \quad (6)$$

$$t^2 = F$$

RESULTS AND DISCUSSION

5.1 Frequency response measurement

Through the frequency response measurement, can know the resonance point of various machine tool shafts, and then set filter parameters to suppress the vibration in high frequency areas; pass the set filter parameter values to motor of machine tool, and re-measure frequency response to achieve the waveform of suppressed vibration, by doing so the vibration of the machine can be effectively suppressed while in high-speed processing.

5.1.1 Before filtering adjustment

In the X-axis frequency response measurements before filtering adjustment, its Gain values will fall to -339.5db, 342.9db at the frequency of 375Hz, 750Hz, as shown in Figure 4. The reason of the falling of Gain values may be caused by that machine is transmitting oil or the fan of main shaft motor is running. Therefore, from the measurement of Bode diagram, it can be seen that there will be an instability phenomenon. As shown in Figure 5, can switch the time domain in the Torque Command relative frequency chart to show the feedback input waveforms and corresponding frequencies of Bode diagram.

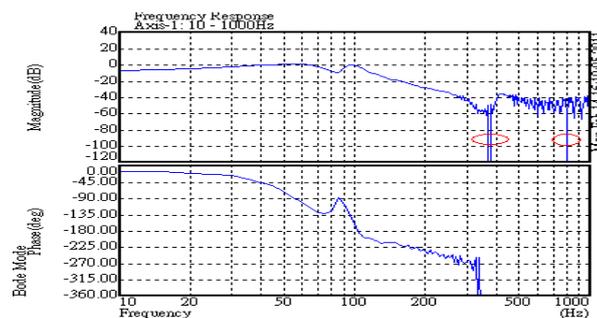


Figure 4 X-axis frequency response measurements before filtering adjustment

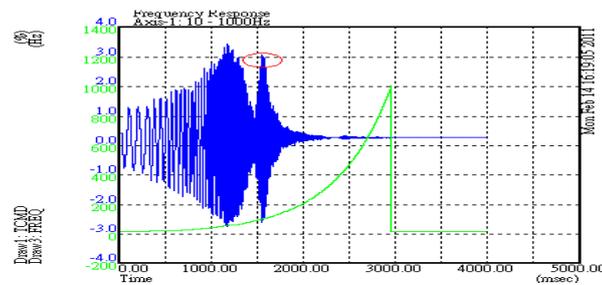


Figure 5 X-axis Torque Command relative frequency chart before filtering adjustment

5.1.2 High frequency filtering to suppress vibration

Utilized vibration damping function, and performed adjustment through using HRV1 filter frequency center parameter (2113), bandwidth parameter (2177), damping coefficient parameter (2359) and HRV2 (2360), (2361), (2362) as listed in Table 2 [14]. As shown in Figure 6, contrast to the case of before filtering adjustment in Figure 7, the frequency response Bode diagram after filtering adjustment did not show obvious lowered Gain values, demonstrating that the filtering adjustment made by us is effective for improving the vibration of machine tools.

Table 2 Filter adjustment

HRV-Filter	Center Frequency (2113)	Bandwidth (2177)	Damping (2359)
HRV1	375	20	15
HRV2	375	50	11

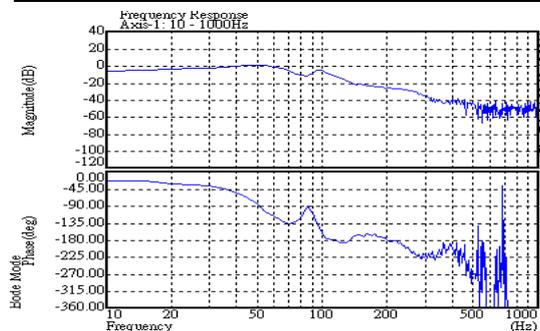


Figure 6 X-axis frequency response measurements after filtering adjustment

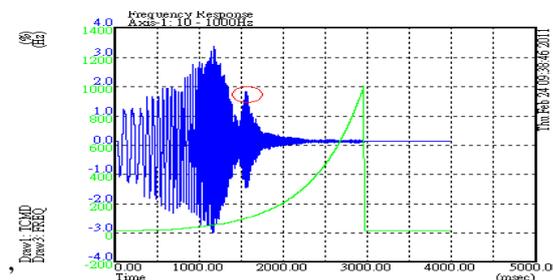


Figure 7 X-axis Torque Command relative frequency chart after filtering adjustment

5.2 Measurement of corner acceleration and deceleration

5.2.1 Experimental parameters screening analysis

In the parameter screening analysis, corner acceleration and deceleration measurements and data analysis were performed as shown in Table 3, the X-axis and Y-axis parameters were actually adjusted on the machine. Through the trajectory chart of corner acceleration and deceleration measurement, it can be clearly seen that the error phenomenon will be generated while in high-speed movement. These errors will have a very big effect on both surface roughness and contour of workpieces while in high-speed cutting. Experimental measurements were conducted according to planned permutations and combinations, then to further understand the effect of these five parameters on corner acceleration and deceleration errors.

Table 3 Corner acceleration and deceleration parameter settings of the machine

Std Other	Run Other	Center Point	Blocks	1768(A)	2021(B)	2092(C)	2109(D)	ERROR
9	1	1	1	16	300	9850	24	0.648333
5	2	1	1	16	300	9950	8	0.616667
4	3	1	1	24	400	9850	8	1.282333
7	4	1	1	16	400	9950	8	0.682
15	5	1	1	16	400	9950	24	0.684
3	6	1	1	16	400	9850	8	0.711
19	7	0	1	20	350	9900	16	0.693
13	8	1	1	16	300	9950	24	0.614333
1	9	1	1	16	300	9850	8	0.648667
14	10	1	1	24	300	9950	24	1.082667
8	11	1	1	24	400	9950	8	1.244667
18	12	0	1	20	350	9900	16	0.683667
6	13	1	1	24	300	9950	8	1.076
17	14	0	1	20	350	9900	16	0.692333
20	15	0	1	20	350	9900	16	0.693
12	16	1	1	24	400	9850	24	1.288333
10	17	1	1	24	300	9850	24	1.113667
16	18	1	1	24	400	9950	24	1.269667
11	19	1	1	16	400	9850	24	0.711
2	20	1	1	24	300	9850	8	1.117

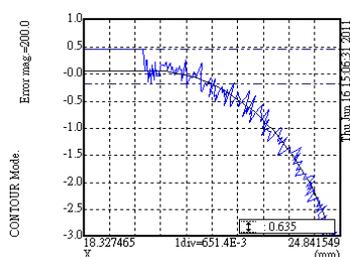


Figure Error in Experiment 1 (Error=0.635μm)

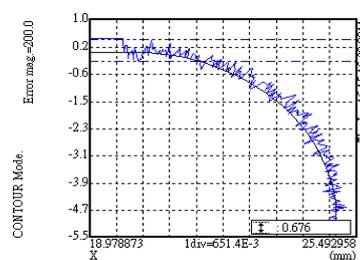


Figure Error in Experiment 5 (Error=0.676μm)

As shown in Figure 8, from the first-order regression model Pareto Chart, the situation of main utility or interaction of control parameter can be understood, its representative factors 1768, 2021 and 2092 have a significant effect, and as shown in the figure, parameter 1768 has biggest effect on the accuracy of corner acceleration and deceleration, then the experimental parameter is A2B2C1. Then carried out residual analysis on constructed regression model to verify whether this regression model is appropriate; from the residual analysis test in Figure 10, it can be viewed that there is no any graphical variation violated the hypothesis, indicating that this configuration mode meets the hypothesis. Distinguished whether the stable point is the easiest method for using maximum value, minimum value to determine the steep descending (ascending) direction, used the completed fitted model to plot contour and response surface diagram and find out the best points, then this is the best combination to make errors optimized, as shown in Figure 11.

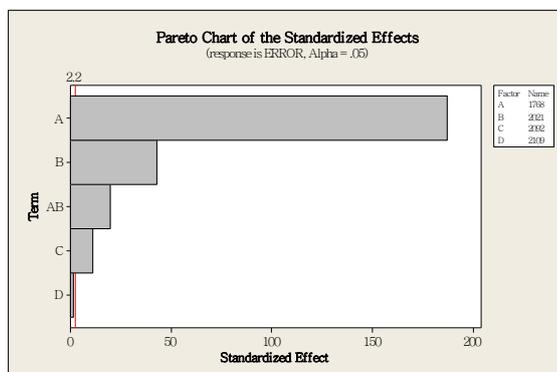


Figure 8 The Pareto Chart of regression model for corner acceleration and deceleration



Figure 9 Main effect analysis diagram

5.2.2 Regression analysis optimization experiment:

Combination of all first-order level factors can fit first-order regression model as follows:

$$y = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 D + \varepsilon \quad (7)$$

A = feed interpolation acceleration / deceleration time constant (1768), B = speed gain (2121), C = feed-forward coefficient (2092), D = fine finishing acceleration / deceleration time constant (2109), conducted first-order model and Lack-of-Fit test:

$$H_0: y = \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 D + \beta_5 E \quad (8)$$

$$H_1: y \neq \beta_0 + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 D + \beta_5 E \quad (9)$$

When using first-order model fitness test, the parameters are A, B, C and D, the P value of this model in Lack-of-Fit test is 0.004, less than $\alpha = 0.05$, experimental parameter design needs to be adjusted, from discriminant 10 it can be learned that the first-order Lack-of-Fit test is H1, therefore this system is a non-linear regression model, the appropriateness of the model can be determined from determinant coefficient R^2 and is 0.9908, the more it is closer to 1, the smaller its error is.

$$F_{(10)} = \frac{0.001109}{0.000021} = 52.81 < F_{(0.05,1,3)}(53.19)$$

When using second-order model fitness test, the parameters are A, B, C and D full mode and interactive, the P value of this model in Lack-of-Fit test is 0.551, larger than $\alpha = 0.05$, is do not reject null hypothesis, from discriminant 11 it can be learned that the first-order Lack-of-Fit test is H1, the appropriateness of the model can be determined from determinant coefficient R^2 and is 0.99.

$$F_{(11)} = \frac{0.00002}{0.000021} = 0.952 < F_{(0.05,5,3)}(0.96)$$

Therefore, used second-order model fitness test, the parameters are A, B, C and AB interactive mode, the P value of this model in Lack-of-Fit test is 0.76, larger than $\alpha = 0.05$, is do not reject null hypothesis, from discriminant 12 it can be learned that the first-order Lack-of-Fit test is H1, the appropriateness of the model can be determined from determinant coefficient R^2 and is 0.99.

$$F_{(12)} = \frac{0.000015}{0.000039} = 0.3846 < F_{(0.05,3,11)}(0.39)$$

Optimized parameters used in second-order model and after conducted experiment obtained the regression equation:

$$y = 3.257 + 0.0173A - 0.00152B - 3.129e-04C + 0.000136AB \quad (13)$$

Conducted analysis and testing In accordance with the best parameters are A2B2C1, then it is able to measure circular error and is $0.608\mu\text{m}$, as shown in the figure, the circular accuracy has reached the optimized improvement.

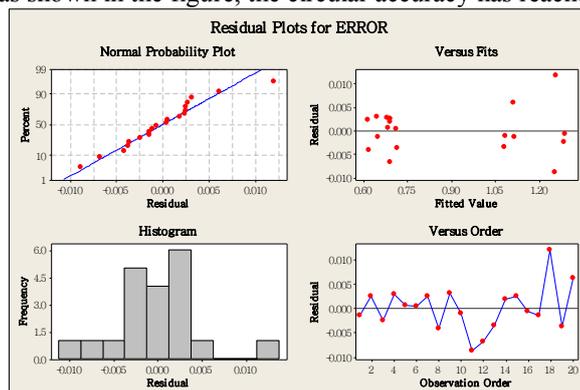


Figure 10 Circular residual analysis chart

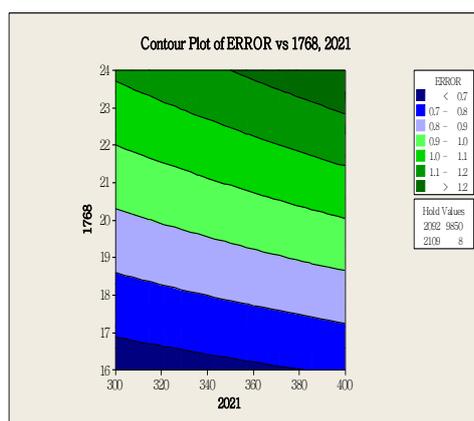


Figure 11 Circular contour chart

5.2.3 Taguchi Method experimental analysis:

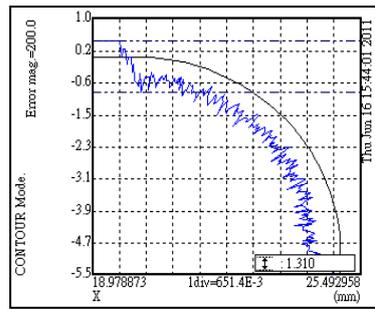
In the third phase, mainly used the regression equation to screen and analyze experimental parameters, and selected important parameters to optimize the design and testing. This experimental test belongs to static S/N ratio of Smaller the Better, five second level control factors can coordinate with L 12 right angle table to conduct analysis, calculated and correspondingly analyzed the output data in accordance with S/N ratio, as shown in figure, its optimized parameters are A2B2C1, as can be learned from table, the parameter 1768 has biggest effect on corner accuracy error, and regression analysis method used the same parameters, its optimized parameters were equally adjusted with regression equation.

Response Table for Means

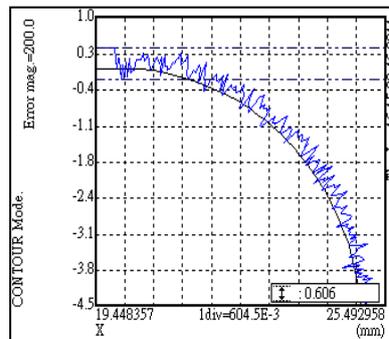
Level	A (1768)	B(2021)	C(2092)
1	0.6647	0.8689	0.9440
2	1.1869	0.9827	0.9076
Delta	0.522	0.1138	0.0365
Rank	1	2	2

5.2.4 Experimental verification:

In the first phase of this study, Regression Analysis Method was adopted to conduct parameter screening; in the second phase, parameter optimization experiment, mainly used Regression Analysis Method and Taguchi Analysis Method to conduct comparison; the feed interpolation acceleration / deceleration time constant (1768) has biggest effect on the corner accuracy, with experimental measurement data unadjusted parameters, after located optimized positioning accuracy according to response surface methodology, compared with experimental data measured before parameter adjustment, from the comparison of measured data and through experimental verification method, it can be learned that the error before adjustment is $1.310\mu\text{m}$, and the accuracy after adjustment is $0.606\mu\text{m}$, as shown in figure..



Accuracy of original parameters



Accuracy after adjusted parameters

CONCLUSION

The following conclusions can be drawn from this study:

1. This study mainly adopted regression equation to conduct the work of parameter screening, avoided the use of the rule of thumb for parameter screening. Through regression analysis, it is learned that the feed interpolation and acceleration / deceleration time constant, the speed gain, and the feed-forward coefficient have bigger effect on corner accuracy error.
2. With respect to the optimization of parameter adjustments, compared regression analysis with Taguchi Method, and through experimental verification method, it can be learned that the error before adjustment is 1.31 μm , and the accuracy after adjustment is 0.606 μm , while the optimized parameters derived from Regression Analysis Method are the same as those from Taguchi Analysis Method.
3. While cutting, the greater the feed interpolation acceleration / deceleration time constant, speed gain, and feed-forward coefficient, the smaller the error of relative cusp, but likely to cause a resonance problem.

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