

Experimental Study On The Identification Model Of Dynamic Milling Force Coefficient

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Abstract. The identification model of milling force coefficient is established using the model of dynamic milling force and the regression analysis of the milling force experiment data. On the basis of the existing milling force model, by simplifying and calculation, it can get the relational expression between milling force coefficient and average value of the milling force. Arranging the milling force experiment and measuring average milling force, the experiment results of milling force coefficient can be calculated. Then, the polynomial expression of identification model of milling force coefficient is established, and its coefficient values can be got by regression analysis. Finally, the accuracy and applicability of the identification model is verified by experiment. The experimental results show that the prediction results of the model are accurate and reliable, and can meet different processing conditions, provide the theoretical basis and reference for the further study of milling process and optimization.

1. Introduction

In the process of metal cutting, the cutting force has a great influence on the machining quality and efficiency. Mechanical model of cutting force is put forward by Sabberwaal[1] firstly, which makes an assumption that the direct proportional for cutting force and the cross-sectional area of chip, and the proportion coefficient depends on the cutting condition and material properties. With the continuous development of machining technology, the cutting force model is improved constantly, and be used in milling. There are many scholars who study on cutting force model and the dynamic cutting process, and put forward a lot of cutting force model under different conditions [2,3,4]. Different cutting force model can be seen theoretically as a function of cutting parameters, cutting condition and the cutting force coefficient [5]. According to different approaches, the coefficient of cutting force has different models, such as: average cutting force coefficient model, bi-linear force model, exponential chip thickness model, semi-mechanic model, high order force model, etc [6]. Coefficient of cutting force can be obtained by the test method, which has two kinds basically, one method can obtain the bevel milling cutting force coefficient through orthogonal cutting database, and another method is a mechanics method that can fast calibrate the coefficient of oblique cutting force [7,8].

2. Identification arithmetic of milling force coefficient

Knowing number of teeth of milling cutter is N , helical angle is β , radius is R , cutting in axial direction is a_p , cutting in radial direction is a_e . The milling cutter is divided to M elements in axial direction.

Through coordinate transformation, by integral operation, the instantaneous cutting force in tangential, radial and axial direction can be rewritten as follows

$$\begin{cases} F_x = \sum_{j=1}^N \sum_{l=1}^M [-dF_{tjl} \cos \phi_{jl} - dF_{rjl} \sin \phi_{jl}] \\ F_y = \sum_{j=1}^N \sum_{l=1}^M [dF_{tjl} \sin \phi_{jl} - dF_{rjl} \cos \phi_{jl}] \\ F_z = \sum_{j=1}^N \sum_{l=1}^M [dF_{ajl}] \end{cases} \quad (1)$$

Where ϕ_{jl} is the instantaneous radial contact angle at teeth j and element l , dF_{tjl} , dF_{rjl} , dF_{ajl} is respectively the force element on the cutter tooth j , thickness d_z and cutting edge l in tangential, radial and axial direction

In the process of milling, the cutting edge works in effective contact interval $\phi_{st} \leq \phi_j \leq \phi_{ex}$, the instantaneous cutting force is integrated in a period of principal axis, and the results calculated by dividing the tooth-spacing angle, so the average cutting force in a period can be got for each tooth. This paper only study on milling force coefficient in tangential and radial direction, so only considering the milling force in X and Y direction. In the case of no spiral Angle and straight tooth cutting, by integral operation, the average cutting force can be written as follows.

$$\begin{cases} \bar{F}_x = \left\{ \frac{Na_p f_t}{8\pi} [K_{tc} \cos 2\phi + K_{rc} (2\phi + \sin 2\phi)] \right\}_{\phi_{st}}^{\phi_{ex}} \\ \bar{F}_y = \left\{ \frac{Na_p f_t}{8\pi} [K_{tc} (2\phi + \sin 2\phi) - K_{rc} \cos 2\phi] \right\}_{\phi_{st}}^{\phi_{ex}} \end{cases} \quad (2)$$

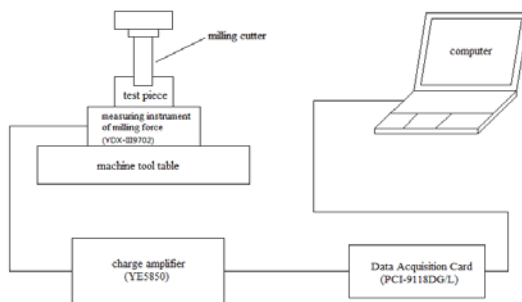
In this paper, with the milling cutter witch has straight tooth and no eccentricity for milling experiments, the entry angle is $\phi_{st} = \arcsin \frac{R - a_e}{R}$, and exit angle is $\phi_{ex} = \frac{\pi}{2}$, so (9) can be rewritten as

$$\begin{cases} \bar{F}_x = -\frac{Na_p f_t}{8\pi} (1 + \cos 2\phi_{st}) K_{tc} + \frac{Na_p f_t}{8\pi} (\pi - 2\phi_{st} - \sin 2\phi_{st}) K_{rc} \\ \bar{F}_y = \frac{Na_p f_t}{8\pi} (\pi - 2\phi_{st} - \sin 2\phi_{st}) K_{tc} + \frac{Na_p f_t}{8\pi} (1 + \cos 2\phi_{st}) K_{rc} \end{cases} \quad (3)$$

3. The milling force experiment

3.1 The experimental and results.

The experimental conditions as follows. The machine tool is four axis linkage vertical machining center YCM-V65A, the Milling dynamometer is YDX-III9702. The material of test piece is 45 # steel. Cutter teeth are 4, cutter diameter is 22 mm, cutter materials for high speed steel, and cutter Angle is 30 °. Cutting conditions is climb and dry milling. Experiment principle and the experiment scene as shown in figure 1.



(a) Measuring principle



(b) Measuring scene

Fig. 1 Measuring principle and measuring scene

This experiment is arranged based on orthogonal table $L_9(3^4)$, and the experimental results as shown in table 1.

Table 1 Experimental arrangement for milling force

test number	$n / (r / \text{min})$	$f_t / (mm / z)$	a_p / mm	a_e / mm	\bar{F}_x / N	\bar{F}_y / N	$K_{tc} / (N / mm^2)$	$K_{rc} / (N / mm^2)$
1-1	600	0.016	4	0.12	-13.83	21.12	17022	19285
1-2	600	0.022	5	0.16	-19.57	31.70	11204	12650
1-3	600	0.028	6	0.20	-24.63	41.48	7436	8039
1-4	700	0.016	5	0.20	-22.20	34.96	13650	14699
1-5	700	0.022	6	0.12	-22.34	39.09	13789	17533
1-6	700	0.028	4	0.16	-17.21	25.79	9374	9801
1-7	800	0.016	6	0.16	-24.75	43.21	15845	18757
1-8	800	0.022	4	0.20	-19.05	28.65	10735	11283
1-9	800	0.028	5	0.12	-20.29	33.05	11804	13745

3.2 Identification model of milling force coefficient.

Accoding to the references [9], the identification model of the dynamic milling force coefficient, can be written as

$$\begin{cases} K_{tc} = a_0 + a_1 a_p + a_2 f_t + a_3 a_e + a_4 a_p^2 + a_5 f_t^2 + a_6 a_e^2 \\ \quad + a_7 a_p n + a_8 a_p f_t + a_9 a_p a_e + a_{10} f_t a_e \\ K_{rc} = b_0 + b_1 a_p + b_2 f_t + b_3 a_e + b_4 a_p^2 + b_5 f_t^2 + b_6 a_e^2 \\ \quad + b_7 a_p n + b_8 a_p f_t + b_9 a_p a_e + b_{10} f_t a_e \end{cases} \quad (4)$$

Where $a_0, a_1, \dots, a_{10}, b_0, b_1, \dots, b_{10}$ is regression coefficient.

MATLAB software is used to make least squares regression analysis [10], result the regression coefficient for the identification model of milling force coefficient, its value as shown in table 2.

Table 2 value of regression coefficient

regression coefficient	value	regression coefficient	value
a_0	50101.2106	b_0	47995.7136
a_1	-3408.5842	b_1	958.1191
a_2	-1105254.3287	b_2	-1603279.2422
a_3	-129648.4762	b_3	-149736.1128
a_4	260.5664	b_4	4.9877
a_5	14975062.8076	b_5	17002187.0256
a_6	240426.2705	b_6	209832.1165
a_7	1.0487	b_7	1.6711
a_8	-9583.2151	b_8	-12983.8779
a_9	2504.8629	b_9	-6024.6818
a_{10}	-179665.3382	b_{10}	1992548.7064

To verify the accuracy and practicability of the milling force coefficient model, additional milling force experiments are arranged, then comparing the experiment value (\bar{F}_x 、 \bar{F}_y) and the predicted value (\bar{F}'_x 、 \bar{F}'_y) of milling force. Experimental conditions as stated in section 3.1, the experimental arrangement and the results as shown in table 3.

Table 3 Experimental arrangement for model verification

test number	$n / (r / \text{min})$	$f_t / (mm / z)$	a_p / mm	a_e / mm	\bar{F}_x / N	\bar{F}'_x / N	\bar{F}_y / N	\bar{F}'_y / N
2-1	500	0.012	3	0.08	-7.41	-7.57	10.14	10.5
2-2	550	0.014	3.5	0.10	-10.36	-10.74	15.05	15.71
2-3	650	0.018	4.5	0.14	-16.66	-17.4	27.30	27.98
2-4	750	0.026	5.5	0.18	-24.11	-24.44	41.97	42.55
2-5	850	0.030	6.5	0.22	-34.26	-35.7	62.41	63.24
2-6	900	0.032	7	0.24	-32.95	-33.31	59.21	62.83

Seeing from table 3, the experimental value and the calculated value of average milling force in X and Y direction is relatively close, it can be calculated that the maximum error respectively is 4.25% and 5.76%, the average error respectively is 2.73% and 3.08%, so the model this paper has established has higher accuracy and better applicability for predicting the milling force.

4. Summary

This paper presents the relational expression between milling force coefficient and average value of the milling force by simplification and calculation based on the existing dynamic milling force model. Through the regression analysis, the identification model of milling force coefficient is established using the experimental data. The experimental verification results show that the experimental value and the calculated value of average milling force is relatively close, so the model this paper has established has higher accuracy and better applicability. The research results can be used in the milling process simulation and other related problems, and provide the theoretical basis and reference for further study and optimization of milling force model.

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