Constraint Control of Milling Stability of Complex Surface Workpiece Based on Parameter Depth Fusion

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Abstract. In order to improve the milling stability control ability of the workpiece, the machining accuracy is not high because of the vibration of the cutter teeth. A constrained control method for milling stability of complex surface workpieces based on parameter depth fusion is proposed. The dynamic change model of cutting parameters of complex curved workpiece is constructed, and the characteristic point distribution model of milling vibration is constructed in the contact region of cutter and workpiece. The maximum tool size and the shortest tool effective length are calculated for each feature point, and the minimum value is chosen among the maximum tool sizes at all feature points. The cutting stability region with dynamic variation of cutting parameters is designed as a set of dynamic constraint parameters. The stability analysis and the depth fusion of cutting parameter optimization model are realized. According to the result of parameter fusion, the error and sensitivity analysis of milling parameters of curved surface workpiece are carried out, and the final optimization parameters of milling tool are obtained. The simulation results show that this method is used to optimize the milling parameters of complex curved surface workpieces, which improves the stability control ability and machining accuracy of the milling process, and the convergence of the tool path error is good.

1. Introductions
The complicated curved surface workpieces contain a lot of workpieces such as gears, turbine blades, engine blades, fan blades, etc. The complex curved surface workpieces have complex structures, long and narrow channels, thin blades and severe bending and torsion, and most of the materials are titanium alloy. High-temperature alloy and other difficult-machining materials, so the complex surface blade processing technology has high requirements [1]. The machining accuracy is not high due to the vibration and flutter of the cutting tool in the machining of complex curved surface, especially in the milling process of this kind of workpiece, the teeth leave ripples on the surface of the workpiece, and the chip is on both sides. The phase difference between ripples leads to regenerative chatter, which limits the quality and precision of machining. The poor process stability is always the channel part that restricts the production of this kind of parts. The control method of property constraint control is used to optimize the machining parameters and to improve the machining process [2].

In the machining process of complex curved workpieces, such as integral blades, impeller and so on, the milling process is usually used to design the curved surface. The selection of process
parameters is the key step in the process planning of complex curved surface machining [3]. The dynamic response characteristics of the blade of the curved surface are combined with the selection of the process parameters. Based on the analysis of the geometric parameters of flexible workpiece, the geometric characteristics of complex surface milling are analyzed, and the reasonable process parameters are selected to improve the productivity and reduce the production cost under the premise of satisfying the machining quality of the parts. In the control of cutting quality of curved workpiece, the dynamic parameters of machine tool affect the final machining effect [4]. Usually, large diameter of cutting tool can improve machining efficiency and stability, but also increase machining stability. The possibility of interference occurs, and small diameter of tool is helpful to avoid interference, but cutting tool breakage is easy to occur in machining process. At present, fuzzy control method and interference control method are mainly used to control the milling stability of complex curved workpiece. Combining with tool feed path optimization, the adaptive parameter fusion and optimal control of workpiece machining are realized. In reference [5], a method based on the combination of critical constraints and dynamic parameters is proposed to optimize the selection of milling parameters for surface workpieces, which can be processed in the feasible range of pendulum cutters. The cutter axis vector is adaptively optimized and the process parameters are optimized by considering the local interference and global interference. However, the steady state error is easy to exist in the tool diameter optimization of curved surface machining using this method. In reference [6], a milling parameter optimization method based on response surface model under the constraint of cutting stability is proposed. The limit cutting depth of curved workpiece machining is taken as the control index of cutting parameter optimization, combined with the machine tool. The coupling relationship between the workpiece and the cutting tool controls the cutting stability, but the method is prone to distortion with the dynamic change of cutting parameters.

In order to solve the above problems, this paper presents an optimization method based on parameter depth fusion for constrained control of machining stability of complex curved workpieces. The dynamic change model of cutting parameters of complex surface workpiece is constructed. The error and sensitivity of milling parameters of curved surface workpiece are analyzed, the final optimization parameters of milling tool are obtained, and the control optimization of milling stability of complex curved workpiece is realized. Finally, the performance test is carried out through the simulation experiment, which shows the superior performance of this method in improving the control stability of machining and milling of complex curved surface workpiece and improving the machining precision.

2. Analysis of dynamic change characteristics of cutting parameters and constraint model of milling stability

2.1. Milling stability constraint model

The position combination of vertical column and spindle box of curved workpiece machining machine tool is taken as an object, on the basis of modeling of spindle, cutter shank and tool joint, the control model of constraint parameter of milling stability is analyzed, and the cutting force is used to control the model [7]. The parameters such as rotational speed and damping ratio are the control constraint parameters. The stability analysis of the machining of curved surface workpiece is carried out. The randomness and non-ergodic property of cutter teeth on the workpiece surface in milling are analyzed, and the multiple machining of curved surface workpiece is obtained. The model of the distribution of body dynamics is defined as follows:

\[ Y_j(n) = W_j^T(n)X(n) + a_j^T(n)Y_{j-1}(n), \quad j < m \]  

(1)

Wherein:

- \( X(n) \) - Input curvature parameters of surface workpiece machining;
$W_j^T(n)$—Characteristic quantity of feed control for principal component $j$;
$a_j^T(n)$—Adjusting weighted value of machine tool parameters of principal component $j$;
$Y_j(n)$—The radius of curvature of principal component $j$;
$Y_j(n)$—Weighted output value of principal component $j$.

According to the result of the phase difference between the two sides of chip and the structural modal analysis method, the steady state characteristic parameter distribution of $j - 1$ principal components of the cutting tool path is obtained:

$$
\begin{align*}
    w_j(x) &= q_k \\
    a_k(x) &= 0 \\
    k &= 1, 2, ..., j - 1
\end{align*}
$$

The dynamic model of multibody flutter for complex surface workpiece is obtained [8].

The dynamic change model of cutting parameters of complex curved workpiece is constructed, and the characteristic point distribution model of milling vibration is constructed in the contact region of cutter and workpiece, as shown in Figure 1.

![Figure 1](image)

2.2. Analysis of dynamic characteristics of cutting parameters

On the basis of the modeling of the spindle-cutting interaction process of the curved workpiece machining, a process reference output model facing the unit cutting process is constructed [9], and the vibration function at the flutter frequency $\omega_c$ is obtained as follows:

$$
\omega_c = \{(k, n), 0 \leq k \leq K, 0 \leq n \leq N\}
$$

Combined with the multi-objective comprehensive optimization method, the dynamic milling equation is obtained as follows:

$$
x_k = \sum_{n=0}^{N-1} C_n \cdot e^{\frac{j2\pi n}{N}} k = 0, 1, \cdots, N - 1
$$

For a discrete rated cutting coefficient distribution matrix, when $n = N$, the transfer function of the contact region of the cutter and workpiece is given as:

$$
Z^N = g \cdot X^N + W^N
$$
Wherein:
\[
Z^N = (z_1, z_2, \ldots, z_N)^T, \quad X^N = (x_1, x_2, \ldots, x_N)^T, \quad W^N = (w_1, w_2, \ldots, w_N)^T
\]
are the motion axis limit vector, curvature interference information vector and global interference vector respectively.

Considering the length of the tool, the maximum tool size and the shortest effective length of the tool are calculated for each feature point is \( (x_i, x_{i+1}, y_i, y_{i+1}) \), \( i = 1, 2, \ldots, n \), Then the surface processing accuracy \( \Sigma \) at the tangent contact C can be expressed as:
\[
\Sigma = \begin{bmatrix} 
\Sigma_i \\
0 \\
0 
\end{bmatrix}
\]

The machining error correction function is \( \Sigma = \text{diag}(\delta), i = 1, 2, \ldots, r \) of tangent contact C under steady state error disturbance.

The cutting stability region with dynamic variation of cutting parameters is designed as a set of dynamic constraint parameters to optimize the tool parameters of milling.

3. Optimization of stability constraint control parameters for milling machining

3.1. Depth fusion of milling parameters for curved workpieces

On the basis of constructing the dynamic change model of cutting parameters of complex curved workpiece and constructing the characteristic point distribution model of milling vibration in the contact region of cutter and workpiece, the optimization control of milling parameters is carried out. A new method based on milling parameters is proposed in this paper. Optimization method of constraint control for machining and milling Stability of complex surface workpiece with parameter depth fusion [10]. The characteristic point distribution model of milling vibration is constructed in the contact region of cutter and workpiece, and the stability functional is carried out by introducing Lyapunov function. The expression is obtained as follows:
\[
\min_{\beta} \| Y(i) - X(i)\| = \min_{\beta} \| X(i+1) - X(i+1)\| \tag{7}
\]
\[
\min_{\beta} \| Y(i) - X(i)\| = \min_{\beta} \begin{bmatrix} 
Y_1 \\
Y_2 \\
\vdots \\
Y_{p(i)} 
\end{bmatrix} - \begin{bmatrix} 
U_1 \Sigma \nu_1 \\
U_2 \Sigma \nu_2 \\
\vdots \\
U_{p(i)} \Sigma \nu_{p(i)} 
\end{bmatrix} \| \tag{8}
\]

According to the relative position of the cutter head, the adaptive control law of two limit cutting depth is obtained by adaptively adjusting the feed path:
\[
f_\varepsilon(X) = w \rho P(X) + w \nu V(X) + w \zeta C(X) + \frac{1}{\varepsilon} [f_\varepsilon(1 - T_{en}/T_{en}) + f_\zeta(1 - \omega_{\zeta}^\text{max}/\omega_{\zeta}) + f_\omega(B_\omega/B_\omega^\text{max} - 1)] \tag{9}
\]

Where, \( \varepsilon \) is a cutting force model coefficient, the maximum tool size allowed for each characteristic point is calculated. When the steady-state feed error of the tool approaches zero, the critical axial cutting depth control error is obtained as \( \varepsilon = x - x_{d}, \varepsilon = \theta - \theta_{d} \), the control error of critical axial cutting depth is obtained:
\[ \begin{align*}
    \dot{x}_1 &= x_3 \\
    \dot{x}_3 &= f_\theta(X,t) + g_\theta(X,t)u(t) + d_\theta(t) \\
    \dot{x}_2 &= x_4 \\
    \dot{x}_4 &= f_(X,t) + g_(X,t)u(t) + d_(t)
\end{align*} \] (10)

Wherein: \( X = [\theta, x, \dot{\theta}, x]^T \), \( f_\theta(X,t) \), \( g_\theta(X,t) \), \( f_\phi(X,t) \), \( g_\phi(X,t) \) represents the transfer functions of the tool-workpiece contact area. \( d_\theta(t) \), \( d_\phi(t) \) takes into account the jitter kinetic energy and potential energy function in the presence of small perturbations. The depth fusion equation of milling parameters for curved surface workpieces is obtained as follows:

\[
    C_f = \begin{cases} 
    0.5150 \frac{(l_g/l_e)^{0.3}}{R_e^{0.15}} & 500 < R_e < 10^4 \\
    0.0325 \frac{(l_g/l_e)^{0.3}}{R_e^{0.15}} & 10^4 < R_e
    \end{cases} \] (11)

According to the fusion results of milling parameters above, the cutting stability region with the dynamic change of cutting parameters is designed as a set of dynamic constraint parameters, and the adaptive optimal selection of control parameters is carried out.

### 3.2. Error control and stability analysis of milling parameters for surface workpiece machining

The cutting stability region with dynamic variation of cutting parameters is designed as a set of dynamic constraint parameters to realize the deep fusion of stability analysis and cutting parameter optimization model, and the transfer function of the process system model is obtained:

\[
    h(t) = \sum_i a_i(t) \delta(t - iT_s)
\] (12)

In the case of determination of radial cutting depth \( y_j(n) \), the critical axial cutting depth vector \( f_j(n) \) has a linear correlation with the cutter’s feed radius \( x(n) \), and the control response function of milling stability in the contact region of the workpiece is obtained as follows:

\[
    \hat{h}_j = \frac{1}{\sigma^2} R_{x}(K-1)f_j(n)
\] (13)

In the formula, \( \sigma^2 \) is the variance of the radial component \( y_j(n) \) of the parameter optimization model, \( R_{x}(k) \) is the tool life correlation coefficient, and the dynamic milling equation is substituted. The results are as follows:

\[
    \sigma^2_j = E[y_j^T(n)y_j(n)]
\] (14)

\[
    R_{x}(k) = E[X(n)X^T(n-k)]
\] (15)

Where \( X(n) \) represents the Toeplitz matrix of \( x(n) \). The error correction iterative function of directional cutting under inherent constraints is obtained as follows:
While \( E[|e(n)|^2] \leq K \), the error correction of milling parameters to curved surface workpiece is obtained as:

\[
f_y(n+1) = f_y(n) + \beta \left[ 1 - \exp(-\alpha_1 \epsilon_{\text{MCMA}}(n)^2) \right] x_i(n) \times \left( \left| y_{e,i}(n) \right|^2 - R_{z,i} y_{e,i}(n)^* + j \left| y_{e,i}(n) \right|^2 - R_{z,i} y_{e,i}(n)^* \right)
\] (16)

According to the above algorithm design, the milling parameter stability constraint control of curved surface workpiece machining is realized, and the schematic diagram of machining error control curve is obtained as shown in figure 2.

![Machining error control curve](image1)

Figure. 2 Machining error control curve

4. Simulation experiment and result analysis

In order to test the application performance of this method in the optimization control of cutting parameters of complex curved workpiece, the simulation experiment is carried out. The material of the workpiece is 45 tempered steel, the cutting force coefficient is 2.893 N/mm2, radial cutting depth 3mm, angle depth is \( u = 0.34 \), initialize radius \( R=0 \), minimum effective tool length is 76mm, process parameter modal parameter is expressed in table 1.

| Radial cutting depth /mm | Large end modulus | Damping ratio | Rigidity /N.s |
|--------------------------|-------------------|--------------|---------------|
| 5                        | 3                 | 0.04         | 10            |
| 8                        | 6                 | 0.08         | 12            |
| 10                       | 8                 | 0.76         | 15            |
| 12                       | 9                 | 0.60         | 18            |

According to the above parameters, the milling tool parameter stability control is carried out. The experimental scene is shown in figure 3.

![Experimental scene](image2)

Figure. 3 Experimental scene
The dynamic change model of cutting parameters of complex surface workpiece is constructed, and the parameter fusion and optimization control of workpiece machining are carried out. Under different radial cutting depth, the control parameter model of cutting parameter is obtained by using the method of this paper and the traditional method, as shown in Figure 4.

Analysis of figure 4 shows that the method of this paper is used to control the stability of machining and milling of complex curved workpiece. With the increasing of limit cutting depth, the reference value of cutting parameters converges to the optimal solution, and the convergence of the control is good. The control design of milling machining is carried out by different methods, and the results of machining accuracy comparison are shown in Figure 5. The analysis figure 5 shows that the error convergence and machining accuracy of the method are good.

5. Conclusions
In the machining process of impeller and so on, milling is usually used to design the curved surface. The selection of process parameters is the key step in the process planning of complex surface machining. In this paper, a complex process based on the deep fusion of parameters is proposed. Optimization method for Stability Control of Surface workpiece Machining and Milling. The dynamic
change model of cutting parameters of complex surface workpiece is constructed, and the feature point distribution model of milling vibration is constructed in the contact region of cutter and workpiece. The maximum tool size and the shortest effective length of tool are calculated for each characteristic point. The cutting stability region with dynamic variation of cutting parameters is designed as a set of dynamic constraint parameters to realize stability analysis and depth melting of cutting parameter optimization model. According to the result of parameter fusion, the error and sensitivity of milling parameters of curved surface workpiece are analyzed, the final optimization parameters of milling tool are obtained, and the control optimization of milling stability of complex curved workpiece is realized. The results show that the proposed method can improve the convergence and precision of complex surface milling, and its performance is better than that of the traditional method.

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