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圆柱齿轮滚齿切削力的预测

张荣闯¹, 黎柏春², 张景强³

(1. 东北大学秦皇岛分校 控制工程学院, 河北 秦皇岛 066004; 2. 东北大学 机械工程与自动化学院, 辽宁 沈阳 110819;
3. 沈阳航空航天大学 机电工程学院, 辽宁 沈阳 110136)

摘 要: 切削力是滚齿工艺参数优化、刀具磨损预测和机床设计的重要依据。针对圆柱齿轮滚齿加工, 提出了一种基于实体建模技术的切削过程几何仿真方法, 实现了未变形切屑的准确提取, 进而计算出未变形切屑厚度。基于微分离散思想, 将滚刀刀齿切削刃离散成一系列微元切削刃, 采用 Kienzle-Victor 力模型, 建立微元切削力模型, 进而构建整体滚刀切削力模型。结合 Kistler 9123C 旋转测力仪和 DMU50 五轴立式加工中心进行滚齿切削力测量试验, 试验结果表明, 预测的滚削力在幅值和变化趋势上与试验测量结果吻合良好, 验证了该滚削力预测方法的有效性。

关键词: 滚齿; 切削力; 实体建模; 未变形切屑厚度; 几何仿真

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Prediction of Cutting Forces in Gear Hobbing of Cylindrical Gears

ZHANG Rong-chuang¹, LI Bai-chun², ZHANG Jing-qiang³

(1. School of Control Engineering, Northeastern University at Qinhuangdao, Qinhuangdao 066004, China; 2. School of Mechanical Engineering & Automation, Northeastern University, Shenyang 110819, China; 3. School of Mechatronics Engineering, Shenyang Aerospace University, Shenyang 110136, China. Corresponding author: ZHANG Rong-chuang, E-mail: zhangrongchuang@neuq.edu.cn)

Abstract: The cutting forces involved during gear hobbing play an important role in process parameter optimization, hob wear prediction and hobbing machine design. The geometrical simulation of the gear hobbing process based on solid modelling was realized. Solid chips were extracted accurately and undeformed chip thickness was calculated. To model the hobbing process, the tool cutting edge was divided into small differential cutting edge segments. The cutting forces exerted on each cutting edge element were calculated based on Kienzle-Victor's equations and the total force components acting on the hob were obtained by integrating the elementary force components. To validate the predictive model of gear cutting forces, the experiments were carried out in DMU50 five-axis CNC machining center equipped with a Kistler 9123C rotary dynamometer. The simulation results are compared with the experiments. The cutting process is well captured by the predictive model, and good correlations in cutting forces are observed between the predictions and experiments.

Key words: gear hobbing; cutting force; solid modelling; undeformed chip thickness; geometrical simulation

高精度圆柱齿轮是高性能齿轮传动系统的重要组成部分。在圆柱齿轮加工方法中, 滚齿加工是一种被广泛应用的粗加工方法, 滚齿切削力是

表征加工过程的一个重要物理参数。实现滚削力的准确预测是研究滚刀磨损与切削振动特性以及切削参数优化的关键理论基础和依据^[1]。

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作者简介: 张荣闯(1984-), 男, 辽宁辽阳人, 东北大学秦皇岛分校讲师, 博士。

Umezaki 等利用解析法分析滚齿切削过程, 综合考虑切屑流动方向、连续/断续切削对切削力系数的影响, 计算出整体滚刀的切削力^[2]. Aboud 建立一个功能运动模型来模拟滚齿切削过程, 利用数值计算方法求出未变形切屑厚度, 进而构建出瞬时滚削力学模型, 并通过试验进行验证^[3]. Klocke 等基于空间离散方法开发出滚齿切削仿真软件 SPARTApro, 实现切削力精确计算^[4]. Tapoglou 等利用 CAD 软件模拟滚齿切削过程, 计算出切削过程几何参量, 结合 Kienzle - Victor 力学模型, 预测出单齿和整体滚刀切削力^[5]. Sabkhi 等借助 CAD 软件计算出滚齿切削未变形切屑厚度, 基于 ALE 法确定切削力系数, 进而计算出滚削力^[6]. Bouzakis 等通过集成仿真环境对滚齿加工中切屑形成机制进行仿真, 同时对切削过程中的切削温度和应力进行了预测^[7]. Friderikos 等为研究高速钢滚刀的崩刃现象, 利用三维刚黏塑性有限元方法对切屑形成过程进行仿真, 明确了切屑挤压现象产生的机理, 获取了切屑形成过程中的应力、应变等物理量^[8]. Stark 等为确定导致齿轮加工过程热变形的热流密度, 通过有限元仿真软件对飞刀切齿过程切削力和切削温度进行仿真和试验验证^[9]. Liu 等利用有限元软件 Third Wave AdvantEdge 对滚齿加工过程中的切削力进行仿真, 并通过单齿铣削力试验进行验证^[10]. Habibi 等基于空间离散法构建端面滚齿切削过程, 实现未变形切屑有效提取, 结合斜角切削理论计算切削力^[11].

本文在已有的基于实体建模的滚齿切削过程仿真研究基础上, 将滚刀切削刃离散为微元切削刃, 构建微元切削力, 进而通过积分、求和运算获得整体滚刀的滚齿切削力预测模型; 便于滚齿切削力测量, 结合 Kistler 9123C 旋转测力仪和 DMU50 五轴数控加工中心进行滚齿切削力测量试验, 试验结果验证了该滚削力建模方法的有效性.

1 滚齿切削过程建模

1.1 切削过程几何仿真

图 1 所示, 与常规的铣削和车削等加工方式不同, 滚齿切削中滚刀轴向进给的同时与工件也必须保持严格的展成运动关系, 具有多刃断续切削和变切屑厚度的特点, 属于典型的非自由切削; 针对滚齿切削, 作者前期研究中^[12-13] 构建了基于实体建模技术的滚齿切削几何仿真模型, 该模型

准确描述滚刀上任意一刀齿的材料去除过程和精确计算出未变形切屑厚度.

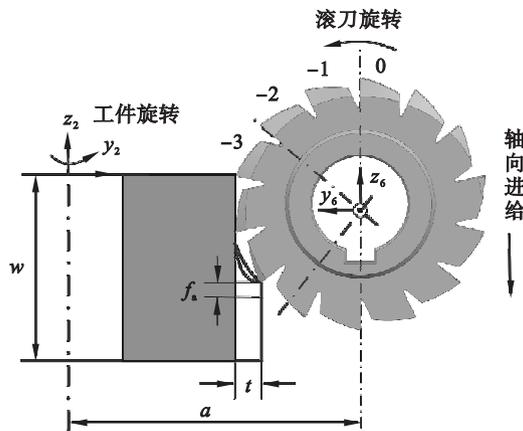


图 1 滚齿切削运动示意图

Fig. 1 Basic kinematics of gear hobbing

1.2 切削力建模

本文采用 Kienzle - Victor 力学模型计算切削力, 则滚刀刀齿切削刃上每一微元切削力表示为

$$\left. \begin{aligned} dF_t(k, i) &= K_t h(k, i)^{1-m_t} db, \\ dF_r(k, i) &= K_r h(k, i)^{1-m_r} db, \\ dF_a(k, i) &= K_a h(k, i)^{1-m_a} db. \end{aligned} \right\} \quad (1)$$

式中: $dF_t(k, i)$, $dF_r(k, i)$, $dF_a(k, i)$ 分别表示滚刀第 k 个刀齿切削刃上第 i 个微元切向、径向、轴向切削力; K_t , K_r 和 K_a 为切削力系数; m_t , m_r 和 m_a 为切屑厚度指数.

由图 2 所示, 微元切削力的方向与参与微元切削刃的位置有关, 通过投影可以得到第 k 个刀齿坐标系 $O_{hk} x_{hk} y_{hk} z_{hk}$ 下切削刃上第 i 个微元切削力:

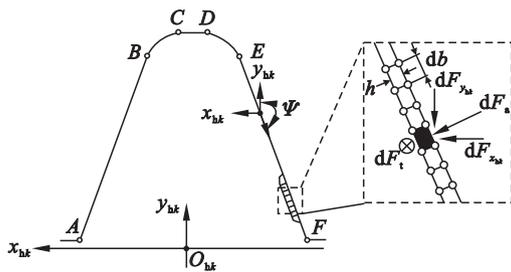


图 2 切削刃离散与坐标系

Fig. 2 Cutting edge discretisation and coordinate systems

$$\left. \begin{aligned} dF_{x_{hk}}(k, i) &= -dF_a(k, i) \sin\psi, \\ dF_{y_{hk}}(k, i) &= -dF_a(k, i) \cos\psi, \\ dF_{z_{hk}}(k, i) &= dF_t(k, i). \end{aligned} \right\} \quad (2)$$

ψ 为切削刃位置角, 取值为

$$\psi = \begin{cases} \alpha_x, i \in AB; \\ \alpha_x \sim \pi/2, i \in BC; \\ \pi/2, i \in CD; \\ \pi/2 \sim \pi - \alpha_x, i \in DE; \\ \pi - \alpha_x, i \in EF. \end{cases}$$

式中, α_x 为滚刀刀齿齿形角。

沿切削刃累加求和, 可得 k 号刀齿产生的滚削力, 即

$$\left. \begin{aligned} F_{x_{hk}}(k) &= \sum_{i=1}^n dF_{x_{hk}}(k, i), \\ F_{y_{hk}}(k) &= \sum_{i=1}^n dF_{y_{hk}}(k, i), \\ F_{z_{hk}}(k) &= \sum_{i=1}^n dF_{z_{hk}}(k, i). \end{aligned} \right\} \quad (3)$$

图 3 所示, 经过坐标转换, k 号刀齿切削力在 0 号刀齿坐标系 $O_{h0}, x_{h0}, y_{h0}, z_{h0}$ 的投影表示为

$$\begin{bmatrix} F_{x_{h0}}(k) \\ F_{y_{h0}}(k) \\ F_{z_{h0}}(k) \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \sin\theta_{k,1} & -\cos\theta_{k,1} \\ 0 & \cos\theta_{k,1} & \sin\theta_{k,1} \end{bmatrix} \begin{bmatrix} F_{x_{hk}}(k) \\ F_{y_{hk}}(k) \\ F_{z_{hk}}(k) \end{bmatrix} \quad (4)$$

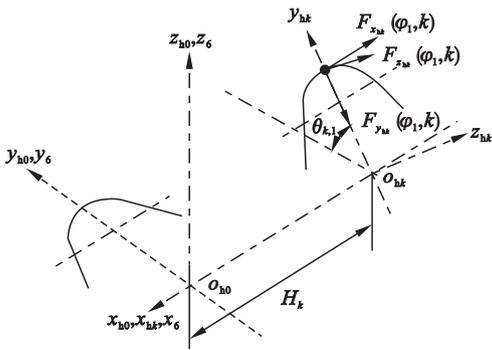


图 3 刀齿坐标系

Fig. 3 Hob tooth coordinate system

将 m 个参与切削刀齿的切削力进行累加求和, 可得整个滚刀在其自身坐标系 O_6, x_6, y_6, z_6 下的瞬时切削力, 即

$$\left. \begin{aligned} F_x &= \sum_{k=1}^m F_{x_{h0}}(k), \\ F_y &= \sum_{k=1}^m F_{y_{h0}}(k), \\ F_z &= \sum_{k=1}^m F_{z_{h0}}(k). \end{aligned} \right\} \quad (5)$$

2 仿真与试验

2.1 仿真与试验参数

为了验证所建立滚削力模型的有效性, 进行

了一系列几何仿真与试验. 仿真与试验所采用滚刀和工件的几何参数, 以及切削参数如表 1 所示. 滚刀前角为 0° 时, 任一微元刃视为直角切削, 此时 $dF_r = K_r = m_r = 0$. 滚刀和工件材料分别为高速钢 6542 和 45 号钢.

表 1 仿真案例几何、切削参数
Table 1 Process parameters for gear hobbing

参数	数值	参数	数值
法向模数 m_n/mm	2	法向压力角 $\alpha_n/(\circ)$	20
齿轮齿数 z	36	齿轮螺旋角 $\beta/(\circ)$	0
齿顶系数 h_a	1	顶隙系数 c	0.25
齿宽 w/mm	30	滚刀前角 $\gamma/(\circ)$	0
铣削方式	顺铣	滚刀旋向	右旋
滚刀头数 N	1	滚刀槽数 Z_k	14
滚刀外径 D_h/mm	71	切削深度 t/mm	4.5
进给量 $f_a/(\text{mm} \cdot \text{r}^{-1})$	1	切削速度 $v/(\text{m} \cdot \text{min}^{-1})$	25

2.2 未变形切屑几何仿真

表 2 所示为通过仿真计算后各刀齿在其展成位置形成的未变形切屑几何实体. 图 4 所示为典型的未变形切屑厚度分布.

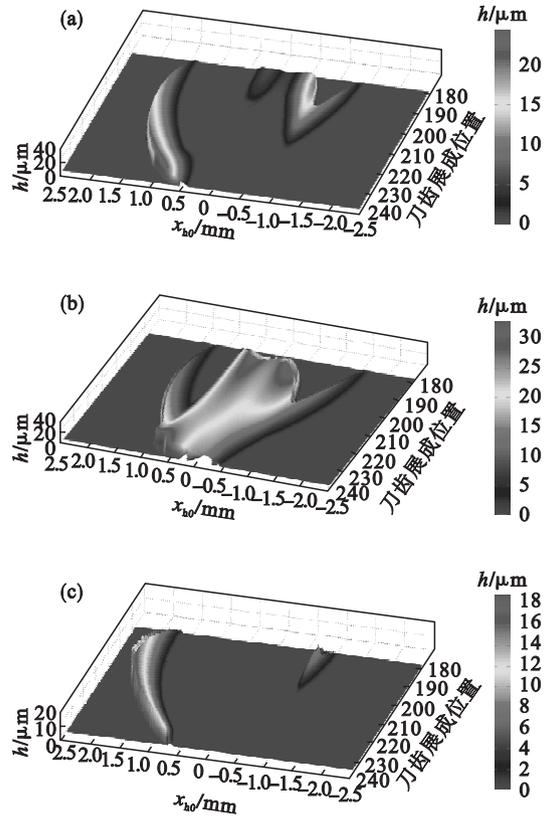


图 4 典型的未变形切屑厚度分布

Fig. 4 Undeformed chip thickness in the typical hob tooth

(a)—0 号刀齿; (b)—6 号刀齿; (c)—11 号刀齿.

表 2 未变形切屑几何实体
Table 2 Undeformed chips for gear hobbing

k	-15	-14	-13	-12	-11	-10	-9	-8	-7	-6
未变形切屑										
k	-5	-4	-3	-2	-1	0	1	2	3	4
未变形切屑										
k	5	6	7	8	9	10	11	12	13	14
未变形切屑										
k	15	16	17	18	19	20	21	22	23	24
未变形切屑										

2.3 滚削力试验设计

滚齿切削力试验所用机床为 DMU50 五轴立式加工中心,旋转测力仪型号为 Kistler9123C. 图 5 所示为滚削力在线采集过程示意图,图 6 所示为滚削力测量现场图.

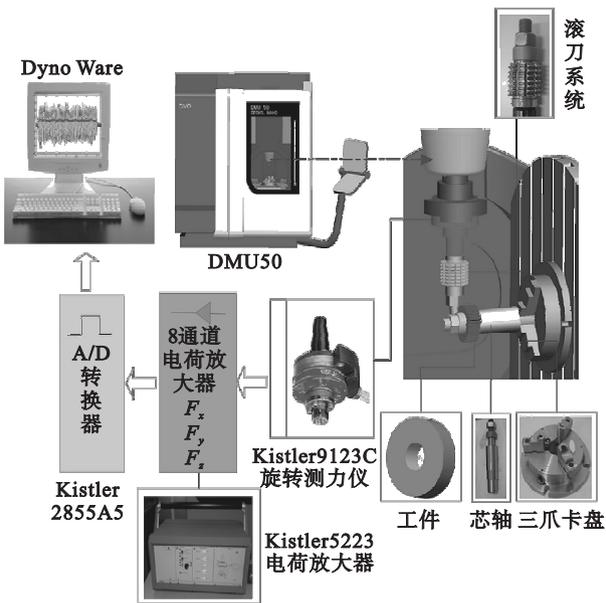


图 5 滚削力在线采集过程示意图

Fig. 5 On-line data acquisition for hobbing forces

2.4 滚削力仿真

采用切削力系数如表 3 所示. 由于滚刀刀齿瞬时切削状态的复杂性,当存在切屑流动干涉时,切削力急剧增加,采用单一切削力系数将会降低切削力预测精度. 因此,本文中未变形切屑厚度在刀齿切削刃上的几何分布为依据,将顶刃、圆弧刃和侧刃同时产生切屑视为存在切屑流动干

涉,采用 1 组切削力系数计算滚削力;否则视为单刃直角切削,采用 2 组切削力系数计算滚削力.

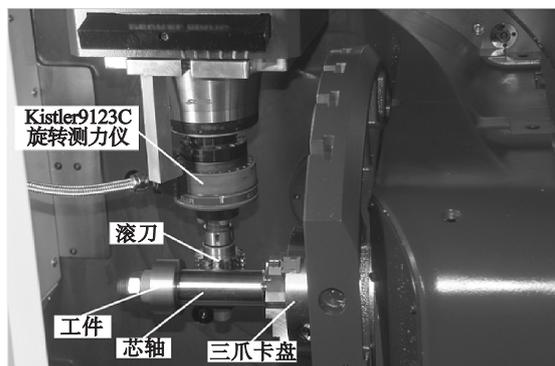


图 6 滚削力测量现场图

Fig. 6 Scene diagram of hobbing force measurement

表 3 切削力系数
Table 3 Cutting force coefficients

组号	$K_t / (N/mm^2)$	m_t	$K_a / (N \cdot mm^{-2})$	m_a
1	1 792	0.198 9	472	0.213 2
2	6 258	0.198 9	3 623	0.213 2

如图 7 所示,为便于与实际测量值进行对比分析,还将式(5)滚削力预测值从滚刀坐标系 $O_6x_6y_6z_6$ 转换到测力仪坐标系 $O_dx_dy_dz_d$ 下,即

$$\left. \begin{aligned} F_{x_d} &= F_y, \\ F_{y_d} &= F_z, \\ F_{z_d} &= -F_x. \end{aligned} \right\} \quad (6)$$

以滚刀旋转一周,即 360° 作为一个切削周期,滚削力的预测值与实测值对比结果如图 8 所示. 从图 8 中可见,切削力 F_{x_d} 和 F_{y_d} 实测值与预测值的波形曲线在形状、变化趋势以及数值上基

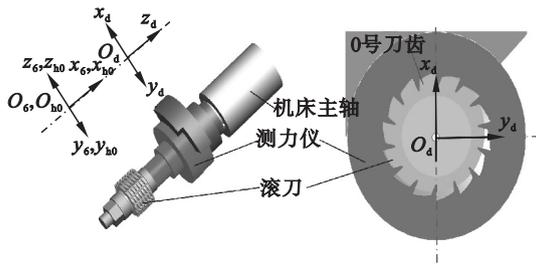
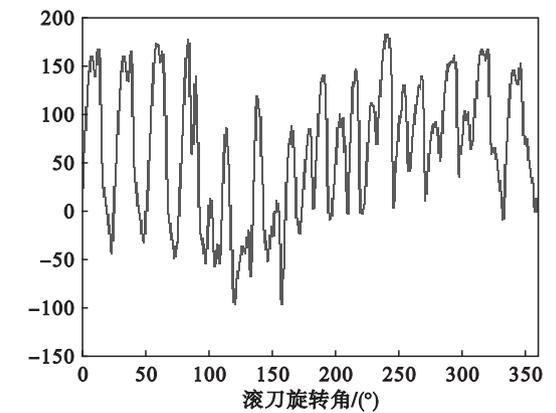
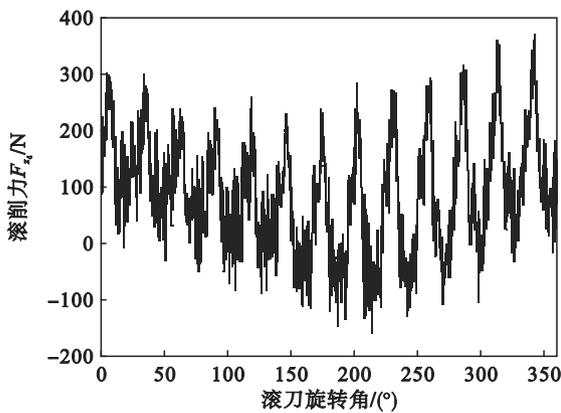
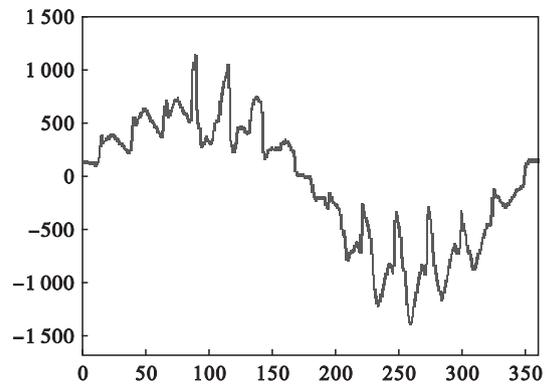
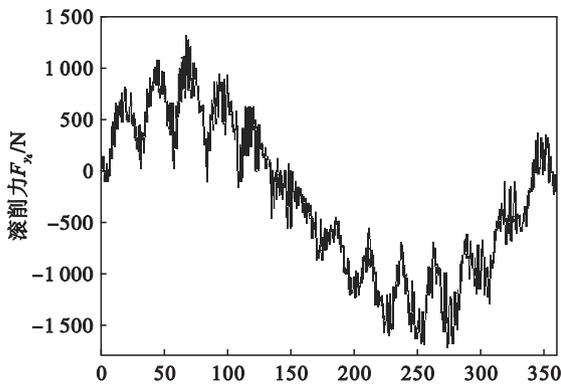
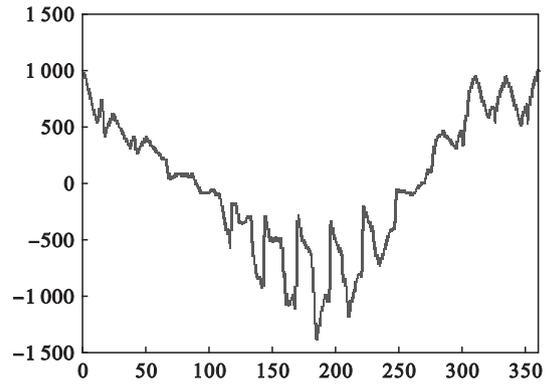
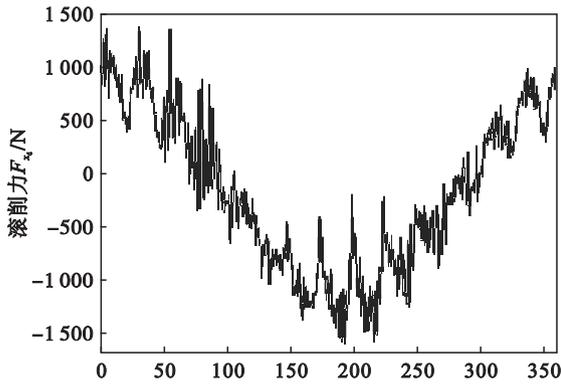


图 7 测力仪坐标系

Fig. 7 Coordinate system of dynamic dynamometer

本一致,但在某些局部区域存在较大差异,其主要是由切削过程中的振动以及预测值中考虑切屑流动干涉采用恒定的切削力系数等因素造成的;这些因素同时也是较小切削力 F_{zd} 的预测值和实测值波形变化规律基本相同而幅值差异较大的主要原因. 总体而言滚削力实测值与预测值在幅值和趋势上吻合良好,证明了该滚削力预报模型的有效性与准确性.



(a)

(b)

图 8 滚削力的预测值和实测值对比

Fig. 8 Comparison between calculated and measured cutting forces in gear hobbing

(a)—实测值; (b)—预测值.

3 结 论

1) 基于实体建模技术建立了滚齿切削过程几何仿真方法,有效地提取出未变形切屑厚度。

2) 基于 Kienzle - Victor 力学模型,结合微分离散的思想,建立了滚齿切削力预测模型。

3) 采用 Kistler9123C 测力仪,结合 DMU50 五轴立式加工中心,构建了滚齿切削力测量方法。

4) 试验结果表明,本文提出的方法能够很好地预测滚齿加工中的切削力幅值及其变化规律。

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