

非正交弧线齿面齿轮齿面设计及根切研究

陈 勇¹, 冯占荣¹, 盛 伟², 王利霞¹, 王文轩¹, 赵玉龙¹

- (1. 南昌航空大学 航空制造工程学院, 南昌 330063;
2. 南京航空航天大学 机电学院, 南京 210016)

摘 要: 非正交弧线齿面齿轮是以端面渐开线弧线齿圆柱齿轮为假想刀具包络展成的面齿轮。根据面齿轮啮合原理推导了非正交弧线齿面齿轮齿面方程,结合 Matlab 数学模型和根切理论研究了该种面齿轮的根切现象,计算出面齿轮不产生根切的最大内径,并通过 Catia 仿真滚齿来验证计算的准确性。该研究旨在提出一种新型非正交面齿轮,通过理论推导及仿真模拟来研究该种面齿轮的根切现象,在此基础上探究非正交弧线齿面齿轮的内径影响因素。研究表明:在同等参数下,当位置参数增大时,刀具渐开线截面高度和内径逐渐减小,当刀具圆弧半径增大时,内径逐渐减小,刀具渐开线截面高度逐渐增大。

关 键 词: 非正交; 弧线齿; 面齿轮; 仿真滚齿; 根切; 最小内径

中图分类号: V232.8 **文献标志码:** A

Research on tooth surface design and undercutting of non-orthogonal arc tooth face-gears

CHEN Yong¹, FENG Zhanrong¹, SHENG Wei², WANG Lixia¹,
WANG Wenxuan¹, ZHAO Yulong¹

- (1. School of Aeronautical Engineering,
Nanchang Hangkong University, Nanchang 330063, China;
2. College of Mechanical Engineering,
Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China)

Abstract: The tooth surface equation of non-orthogonal arc tooth face-gear was derived according to the principle of face-gear meshing. The undercut phenomenon of this type of face-gear was studied by combining Matlab mathematical model with undercut theory, and the maximum internal diameter of face-gear without undercut was calculated. Catia simulation hobbing was used to verify the accuracy of the calculation. A new type of non-orthogonal face-gear was proposed. The undercut phenomenon of this kind of face-gear was studied through theoretical derivation and simulation. Based on this, the factors affecting the internal diameter of non-orthogonal arc tooth face-gears were explored. Results showed that under the same parameters, when the position parameter increased, the height and inner diameter of the involute section of the tool gradually reduced. When the radius of the tool increased, the inner diameter gradually reduced, and the height of the involute section

收稿日期:2019-11-03

基金项目:无损检测教育部重点实验室开放基金(ZD201229010);江西省教育厅科学技术研究项目(GJJ160701)

作者简介:陈勇(1996—),男,硕士生,主要研究方向为机械设计制造。

引用格式:陈勇,冯占荣,盛伟,等.非正交弧线齿面齿轮齿面设计及根切研究[J].航空动力学报,2020,35(5):1081-1088. CHEN Yong,FENG Zhanrong,SHENG Wei,et al. Research on tooth surface design and undercutting of non-orthogonal arc tooth face-gears[J]. Journal of Aerospace Power,2020,35(5):1081-1088.

of the tool gradually increased.

Key words: non-orthogonal; arc tooth; face-gear; simulation of gear hobbing; undercutting; minimum inner radius

面齿轮副^[1-2]是一种与锥齿轮副相似的齿轮传动结构。面齿轮副是由小轮为圆柱齿轮和大轮为面齿轮组成,相比锥齿轮传动而言,面齿轮具有体积小、承载能力强以及拥有较大重合度等特点,这就使得面齿轮在高速、重载的工况下得到广泛使用,现已应用于飞机、车辆以及其他高性能机械装备中。且随着面齿轮的不断发展,许多新型面齿轮也逐渐被设计出来,如直齿面齿轮^[3-7]、斜齿面齿轮^[8-9]、基于刀盘加工的弧线齿面齿轮^[10-12]和蜗杆面齿轮^[13]等。在设计面齿轮时,必须避免根切和齿顶变尖现象,故应将面齿轮齿宽设计在合理的范围内,从而消除根切和齿顶变尖。本文以端面渐开线的弧线齿圆柱齿轮^[14-17]作为假想刀具,推导出非正交弧线齿面齿轮齿面方程,并通过 Matlab 对齿面进行编程得到单齿全齿面数学模型。

1 非正交弧线齿面齿轮齿面方程推导

1.1 弧线齿圆柱齿轮齿面方程

由图 1~图 3 可见,刀具齿轮齿宽为 B ,节圆半径为 R_1 ,齿线 L 为分度圆柱面上的齿槽对称线,圆弧半径为 R_t 。 R_b 是刀具基圆半径, θ_s 是渐开线上任意一点的角度参数, θ_{s0} 是齿槽对称线 Ox 到渐开线起始点的角度参数,平面 Oxy 和平面 $O_sx_sy_s$ 垂直距离为 h , x_s 轴相对于 x 轴

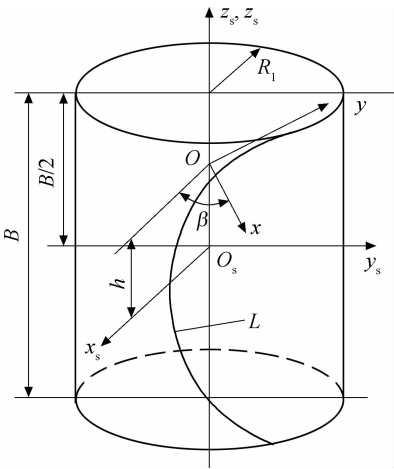


图 1 弧线齿圆柱齿轮坐标系

Fig. 1 Cylindrical gear coordinate system with arc teeth

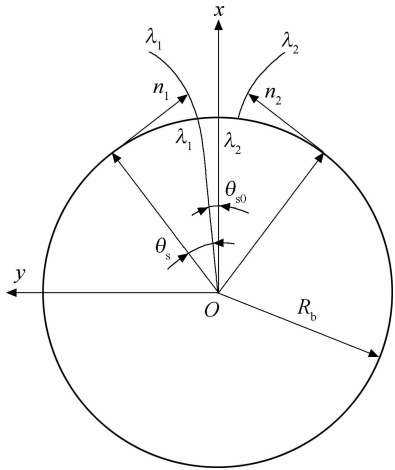


图 2 截面坐标系

Fig. 2 Cross sectional coordinate system

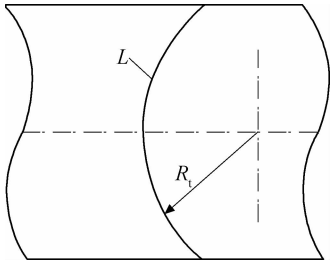


图 3 圆柱齿轮展开图

Fig. 3 Cylindrical gear development diagram

绕 z_s 轴旋转了位置角 β , 刀具两侧渐开线分别为 $\lambda_1-\lambda_1, \lambda_2-\lambda_2$, 与两侧渐开线对应的法向量分别为 n_1, n_2 。

$$\beta = (R_t - \sqrt{R_t^2 - h^2})/R_1 \tag{1}$$

渐开线齿廓方程为

$$\begin{aligned} \mathbf{r}_h(\theta_s) &= (x_h, y_h, z_h, t)^T = \\ &\begin{bmatrix} R_b[\cos(\theta_{s0} + \theta_s) + \theta_s \sin(\theta_{s0} + \theta_s)] \\ \pm R_b[\sin(\theta_{s0} + \theta_s) - \theta_s \cos(\theta_{s0} + \theta_s)] \\ 0 \\ 1 \end{bmatrix} \end{aligned} \tag{2}$$

涉及到的坐标变化为

$$\mathbf{M}_{sh} = \begin{bmatrix} \cos\beta & -\sin\beta & 0 & 0 \\ \sin\beta & \cos\beta & 0 & 0 \\ 0 & 0 & 1 & h \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

刀具齿面方程为

$$\mathbf{r}_s(r_{sx}, r_{sy}, r_{sz}, t)^T = \mathbf{M}_{sh} \mathbf{r}_h =$$
$$\begin{pmatrix} R_b[\cos(\theta_{s0} + \theta_s \pm \beta)] \\ + \theta_s \sin(\theta_{s0} + \theta_s \pm \beta)] \\ \pm R_b[\sin(\theta_{s0} + \theta_s \pm \beta) \\ - \theta_s \cos(\theta_{s0} + \theta_s \pm \beta)] \\ h \\ 1 \end{pmatrix} \quad (4)$$

刀具齿面法向量为

$$\mathbf{n} = \frac{\partial \mathbf{r}_s}{\partial \theta_s} \times \frac{\partial \mathbf{r}_s}{\partial h} = (n_x, n_y, n_z)^T \quad (5)$$

1.2 非正交弧线齿面齿轮全齿面方程推导

如图 4 所示,根据非正交弧线齿面齿轮传动简图建立面齿轮副传动坐标系,如图 5 所示。面齿轮和刀具齿轮的固定坐标系分别为 $O_{20}-x_{20}y_{20}z_{20}$ 、 $O_s-x_sy_sz_s$,动坐标系分别为 $O_2-x_2y_2z_2$ 、 $O_1-x_1y_1z_1$,为了方便面齿轮和假想刀具之间的坐标变换,从而建立中间坐标系 $O_p-x_py_pz_p$,面齿轮与刀具齿轮轴交角为 γ ,刀具与面齿轮传动轴的轴心距为 L_0 ,面齿轮与刀具的角速度分别为 ω_2 、 ω_s 。刀具轴线与面齿轮齿顶平面的距离为 $r_{sm}=R_1-m$,面齿轮与刀具的转动参数分别为 φ_2 、 φ_s 。

图 5 涉及到的坐标变换的矩阵如下:

$$\mathbf{M}_{1,s} = \begin{bmatrix} \cos \phi_s & -\sin \phi_s & 0 & 0 \\ \sin \phi_s & \cos \phi_s & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
$$\mathbf{M}_{p,1} = \begin{bmatrix} 0 & 0 & 1 & L_0 \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

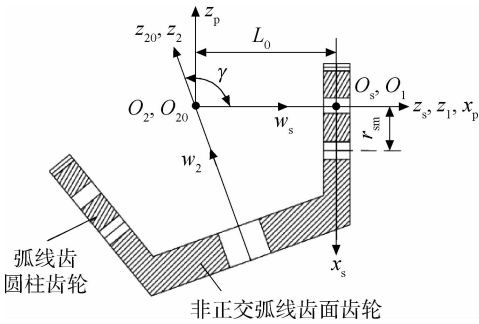


图 4 非正交弧线齿面齿轮传动简图
Fig. 4 Simplified diagram of non-orthogonal arc tooth face-gear transmission

$$\mathbf{M}_{20,p} = \begin{bmatrix} \sin \gamma & 0 & -\cos \gamma & 0 \\ 0 & 1 & 0 & 0 \\ \cos \gamma & 0 & \sin \gamma & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
$$\mathbf{M}_{2,20} = \begin{bmatrix} \cos \phi_2 & \sin \phi_2 & 0 & 0 \\ -\sin \phi_2 & \cos \phi_2 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{M}_{2,s} = \mathbf{M}_{2,20} \cdot \mathbf{M}_{20,p} \cdot \mathbf{M}_{p,1} \cdot \mathbf{M}_{1,s} \quad (6)$$

设接触点沿刀具坐标系运动的速度为 v_s ,随面齿轮坐标系运动的速度为 v_2 ,那么刀具齿轮与面齿轮的齿面接触处的相对速度就是 $v^{(s,2)}$ 。

刀具齿轮与被加工面齿轮齿面相对速度为

$$\mathbf{v}^{(s,2)} = (\omega_s \mathbf{k}_s - \omega_2 \mathbf{k}_2) \times \mathbf{r}_s - \omega_2 \mathbf{k}_2 \times L_0 \mathbf{k}_s =$$
$$(v_x^{(s,2)}, v_y^{(s,2)}, v_z^{(s,2)})^T \quad (7)$$

将式(5)、式(7)代入非正交弧线齿面齿轮啮合方程为

$$f = \mathbf{n} \cdot \mathbf{v}^{(s,2)} =$$
$$n_x \times v_x^{(s,2)} + n_y \times v_y^{(s,2)} + n_z \times v_z^{(s,2)} =$$
$$\sin \phi_s a_0 + \cos \phi_s b_0 - A = 0 \quad (8)$$

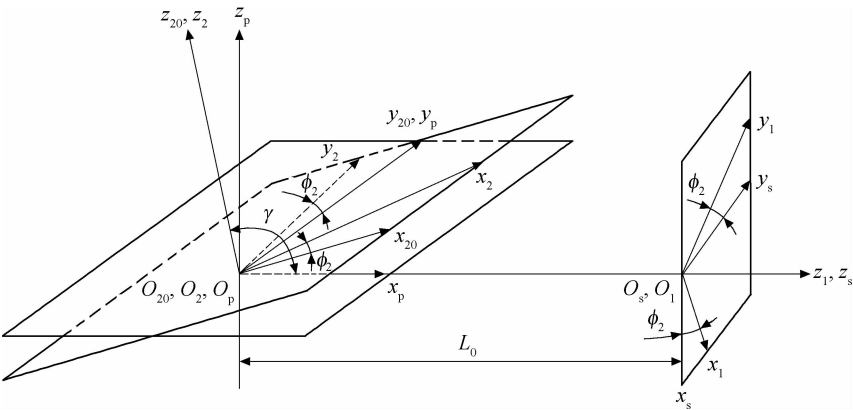


图 5 非正交弧线齿面齿轮坐标系
Fig. 5 Non-orthogonal arc tooth face-gear coordinate system

其中 A 、 a_0 、 b_0 分别为

$$A = \pm r_{sy}(\omega_s - \cos \gamma \omega_2) \sin(\theta_{s0} + \theta_s \pm \beta) +$$
$$r_{sx}(\omega_s - \cos \gamma \omega_2) \cos(\theta_{s0} + \theta_s \pm \beta)$$
$$a_0 = R_b \frac{\partial \beta}{\partial h} \sin \gamma \omega_2 r_{sy} \mp$$
$$\sin \gamma \omega_2 (r_{sz} + L_0) \sin(\theta_{s0} + \theta_s \pm \beta)$$
$$b_0 = R_b \frac{\partial \beta}{\partial h} \sin \gamma \omega_2 r_{sx} +$$
$$\sin \gamma \omega_2 (r_{sz} + L_0) \cos(\theta_{s0} + \theta_s \pm \beta) \quad (9)$$

化简即可得到 ϕ_s 关于 θ_s 、 h 的方程

$$\sqrt{a_0^2 + b_0^2} \sin(\phi_s + t) = A$$
$$t = \arctan \frac{b_0}{a_0}$$
$$\phi_s = \arcsin \left(\frac{A}{\sqrt{a_0^2 + b_0^2}} \right) - t \quad (10)$$

非正交弧线齿面齿轮工作齿面方程

$$\boldsymbol{r}_2 = \boldsymbol{M}_{2s} \boldsymbol{r}_s = (r_{2x}, r_{2y}, r_{2z})^T$$
$$r_{2x} = (\cos \phi_2 \cos \gamma \cos \phi_s + \sin \phi_2 \sin \phi_s) r_{sx} +$$
$$(-\sin \phi_s \cos \phi_2 \cos \gamma + \sin \phi_2 \cos \phi_s) r_{sy} +$$
$$\cos \phi_2 \sin \gamma r_{sz} + \cos \phi_2 \sin \gamma L_0$$
$$r_{2y} = (-\sin \phi_2 \cos \gamma \cos \phi_s + \cos \phi_2 \sin \phi_s) r_{sx} +$$
$$(-\sin \phi_s \sin \phi_2 \cos \gamma + \cos \phi_2 \cos \phi_s) r_{sy} -$$
$$\sin \phi_2 \sin \gamma r_{sz} - \sin \phi_2 \sin \gamma L_0$$
$$r_{2z} = -\cos \phi_s \sin \gamma r_{sx} + \sin \phi_s \sin \gamma r_{sy} +$$
$$\cos \gamma r_{sz} + \cos \gamma L_0 \quad (11)$$

由过渡曲面形成条件,将式(11)与刀具齿顶处的 θ_s 联立,即可求得非正交弧线齿面齿轮过渡曲面方程为

$$\boldsymbol{r}_2^* = \begin{cases} \boldsymbol{r}_2 = \boldsymbol{M}_{2s} \boldsymbol{r}_s \\ \theta_s = \frac{\sqrt{R_a^2 - R_b^2}}{R_b} \end{cases} \quad (12)$$

非正交弧线齿面齿轮设计参数如表 1。

表 1 设计参数

Table 1 Design parameters

参数	数值
模数 m/mm	4
圆柱齿轮齿数 N_s	30
圆柱齿轮压力角 $\alpha_s/(\circ)$	20
圆柱齿轮齿宽 B/mm	100
圆弧半径 R_1/mm	500
面齿轮齿数 N_2	120
位置参数 L_0/mm	240
轴交角 $\gamma/(\circ)$	100

借助 Matlab 将面齿轮单齿全齿面进行可视化是多样的。根据公式(10)中得到的 ϕ_s 、 θ_s 、 h 三个未知量的关系,可任取两个作为离散化取值变量。本文设 ϕ_s 为 θ_s 和 h 的函数,故将 θ_s 和 h 进行离散化取值代入式(11)来对面齿轮的工作齿面进行数学建模如图 6。由于过渡曲面中的 θ_s 为定值,故将 ϕ_s 和 h 离散化取值代入式(12)来建立过渡曲面数学模型如图 7。非正交弧线齿面齿轮单齿全齿面数学模型如图 8。

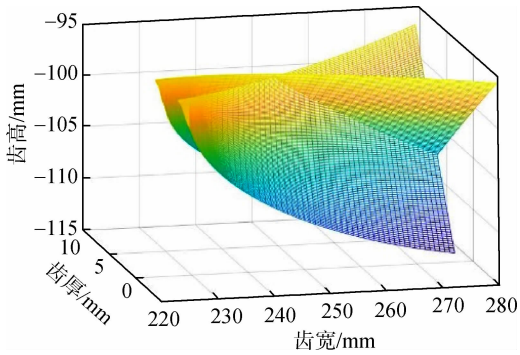


图 6 工作齿面

Fig. 6 Working tooth surface

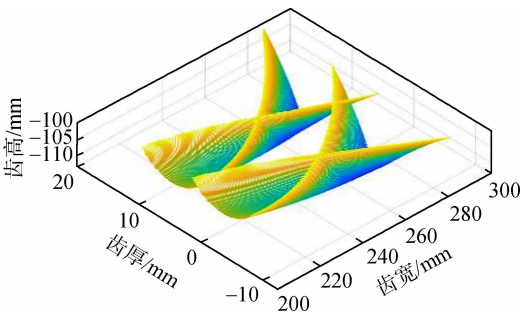


图 7 过渡曲面

Fig. 7 Transition surface

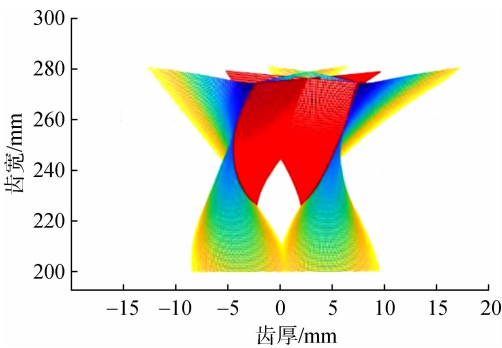


图 8 单齿全齿面

Fig. 8 Single tooth full tooth surface

2 齿根根切

2.1 非正交弧线齿面齿轮根切理论

由齿轮根切理论^[1]可知,当 $v_2=0$ 时,面齿轮齿面将会出现根切点,则与之对应在刀具齿面上存在一条根切界限线,由刀具齿面方程(4)可知 x_s, y_s, z_s 是关于 θ_s 和 h 的函数。

$$v_2 = v_s + v^{(s,2)} = 0 \quad (13)$$

故 v_{sx}, v_{sy}, v_{sz} 与 $v^{(s,2)}, r_s$ 的关系如下:

$$\begin{cases} v_{sx} = -v_x^{(s,2)} = \frac{dx_s}{dt} = \frac{\partial x_s}{\partial \theta_s} \cdot \frac{d\theta_s}{dt} + \frac{\partial x_s}{\partial h} \cdot \frac{dh}{dt} \\ v_{sy} = -v_y^{(s,2)} = \frac{dy_s}{dt} = \frac{\partial y_s}{\partial \theta_s} \cdot \frac{d\theta_s}{dt} + \frac{\partial y_s}{\partial h} \cdot \frac{dh}{dt} \\ v_{sz} = -v_z^{(s,2)} = \frac{dz_s}{dt} = \frac{\partial z_s}{\partial \theta_s} \cdot \frac{d\theta_s}{dt} + \frac{\partial z_s}{\partial h} \cdot \frac{dh}{dt} \end{cases} \quad (14)$$

根据式(14)可知啮合方程式 f 关于 θ_s, h, ϕ_s 的函数,且 f 对任意时刻的 t 都为恒等式,对啮合方程(8)进行微分得

$$\frac{\partial f}{\partial \theta_s} \cdot \frac{d\theta_s}{dt} + \frac{\partial f}{\partial h} \cdot \frac{dh}{dt} + \frac{\partial f}{\partial \phi_s} \cdot \frac{d\phi_s}{dt} = 0 \quad (15)$$

由式(14)、式(15)应可得三个等价的线性方程组,这里选其一为

$$\begin{cases} \frac{\partial x_s}{\partial \theta_s} \cdot \frac{d\theta_s}{dt} + \frac{\partial x_s}{\partial h} \cdot \frac{dh}{dt} = -v_x^{(s,2)} \\ \frac{\partial z_s}{\partial \theta_s} \cdot \frac{d\theta_s}{dt} + \frac{\partial z_s}{\partial h} \cdot \frac{dh}{dt} = -v_z^{(s,2)} \\ \frac{\partial f}{\partial \theta_s} \cdot \frac{d\theta_s}{dt} + \frac{\partial f}{\partial h} \cdot \frac{dh}{dt} = -\frac{\partial f}{\partial \phi_s} \cdot \frac{d\phi_s}{dt} \end{cases} \quad (16)$$

且该线性方程组可表示成系数矩阵 E 和增广矩阵 F 。

$$E = \begin{bmatrix} \frac{\partial x_s}{\partial \theta_s} & \frac{\partial x_s}{\partial h} \\ \frac{\partial z_s}{\partial \theta_s} & \frac{\partial z_s}{\partial h} \\ \frac{\partial f}{\partial \theta_s} & \frac{\partial f}{\partial h} \end{bmatrix}, F = \begin{bmatrix} \frac{\partial f}{\partial \theta_s} & \frac{\partial f}{\partial h} & -\frac{\partial f}{\partial \phi_s} \cdot \frac{d\phi_s}{dt} \\ \frac{\partial x_s}{\partial \theta_s} & \frac{\partial x_s}{\partial h} & -v_x^{(s,2)} \\ \frac{\partial z_s}{\partial \theta_s} & \frac{\partial z_s}{\partial h} & -v_z^{(s,2)} \end{bmatrix} \quad (17)$$

由于系数矩阵 E 的秩小于等于2,故增广矩阵 F 的行列式等于0。

$$|F| = \begin{vmatrix} \frac{\partial f}{\partial \theta_s} & \frac{\partial f}{\partial h} & -\frac{\partial f}{\partial \phi_s} \cdot \frac{d\phi_s}{dt} \\ \frac{\partial x_s}{\partial \theta_s} & \frac{\partial x_s}{\partial h} & -v_x^{(s,2)} \\ \frac{\partial z_s}{\partial \theta_s} & \frac{\partial z_s}{\partial h} & -v_z^{(s,2)} \end{vmatrix} = 0 \quad (18)$$

展开该行列式(18)得

$$\begin{aligned} & \frac{\partial f}{\partial \theta_s} \left(-v_z^{(s,2)} \frac{\partial x_s}{\partial h} + v_x^{(s,2)} \frac{\partial z_s}{\partial h} \right) - \\ & \frac{\partial f}{\partial h} \left(-v_z^{(s,2)} \frac{\partial x_s}{\partial \theta_s} + \frac{\partial z_s}{\partial \theta_s} v_x^{(s,2)} \right) - \\ & \frac{\partial f}{\partial \phi_s} \cdot \frac{d\phi_s}{dt} \left(\frac{\partial x_s}{\partial \theta_s} \cdot \frac{\partial z_s}{\partial h} - \frac{\partial x_s}{\partial h} \cdot \frac{\partial z_s}{\partial \theta_s} \right) = 0 \end{aligned} \quad (19)$$

将根切条件式(18)与啮合方程(8)联立即求得刀具齿轮上的根切界限线,该界限线包含三个未知量 (θ_s, h, ϕ_s) ,由于根切界限线与刀具齿顶圆柱的交点就是根切界限点,刀具齿顶位置处的 θ_s 为

$$\theta_s^* = \frac{\sqrt{R_a^2 - R_b^2}}{R_b} \quad (20)$$

将 θ_s^* 代入式(8)、式(18)联立的方程组内,则可求得对应的 (h, ϕ_s) 值,将求得的 (θ_s, h, ϕ_s) 分别代入两侧工作齿面(11)即可求得面齿轮的根切点 $C(x_2, y_2, z_2)$,如图9所示, R_{in} 是非正交弧线齿面齿轮内径。由于弧线齿面齿轮与直齿面齿轮不同,其单齿两侧并不是呈对称状,应分别对两侧齿面进行内半径设计,取内径较大的一侧为最终内径值。

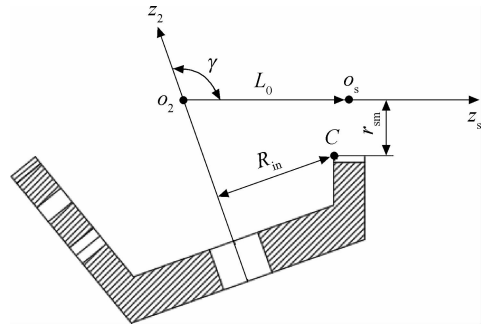


图9 根切简图

Fig. 9 Undercutting diagram

内径计算公式为

$$R_{in} = \sqrt{x_2^2 + y_2^2} \quad (21)$$

由于非正交弧线齿面齿轮齿面方程较为复杂,借助 Matlab 分别求得两侧 R_{in} 的值。表2为求得两侧工作齿面 h, ϕ_s 的值,以及与其对应的 (x_2, y_2, z_2) 及内径值。

由表2及式(21)可得 $R_{in}=227.90\text{ mm}$ 。

非正交弧线齿面齿轮根切位置如图10所示,在设计面齿轮之初应切去根切部分。

表 2 各参变量值
Table 2 Each parameter value

工作齿面	h/mm	$\phi_s/({}^\circ)$	(x_2, y_2, z_2)	R_{in}/mm
凸齿面	0.71	-0.45	(227.88, 2.54, -100.50)	227.90
凹齿面	0.73	0.45	(227.87, -2.55, -100.57)	227.89

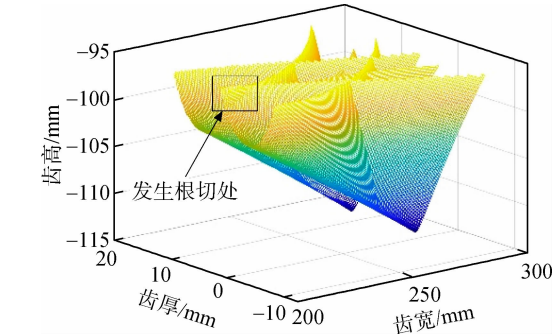


图 10 根切位置
Fig. 10 Undercutting position

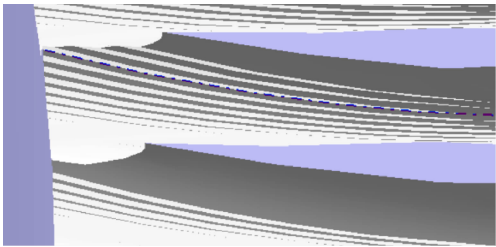


图 12 根切
Fig. 12 Undercutting

2.2 仿真滚齿验证

为了验证上述计算的真实性,本文基于 Catia 二次开发,对非正交弧线齿面齿轮齿坯进行仿真滚齿。如图 11 所示,将刀具与面齿轮按照标准中心距安装,随后根据传动比进行滚齿仿真。从图 12 可以看出在面齿轮内径处发生根切现象,以文中第 2.1 节计算的最大内径为半径做旋转槽,在误差允许的范围内刚好切去根切部分,如图 13。

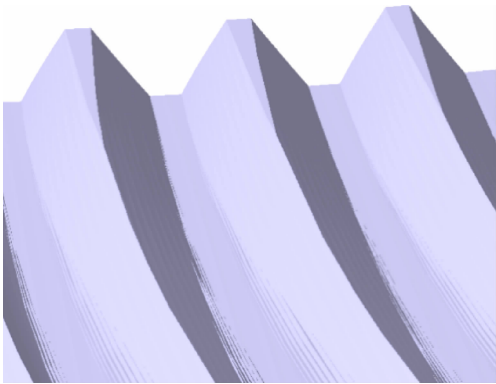


图 13 消除根切
Fig. 13 Eliminate undercutting

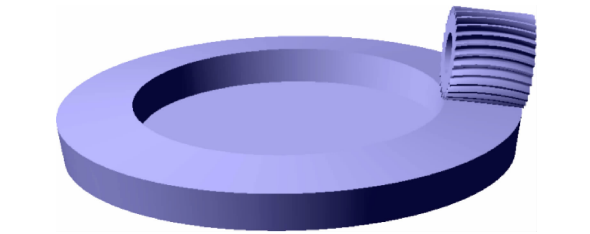


图 11 非正交弧线齿面齿轮齿坯
Fig. 11 Non-orthogonal arc tooth face-gear tooth blank

2.3 内径影响因素

为了找出非正交弧线齿面齿轮不产生根切的最大内径的影响因素,本文通过位置参数 L_0 和刀具圆弧半径的变化来探究对内径的影响。如图 14、图 15 为表 1 所示同等参数下, L_0 对 h 和 R_{in} 的影响。

如图 16、图 17 为表 1 所示同参数下刀具圆弧半径对 h 和 R_{in} 的影响。

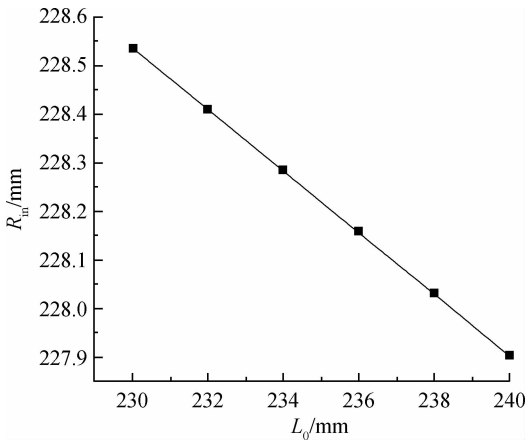


图 14 位置参数 L_0 与 R_{in} 的关系
Fig. 14 Relationship between L_0 and R_{in}

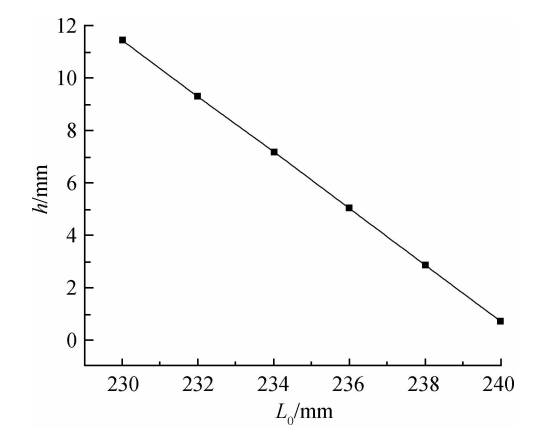


图 15 位置参数 L_0 与 h 的关系

Fig. 15 Relationship between L_0 and h

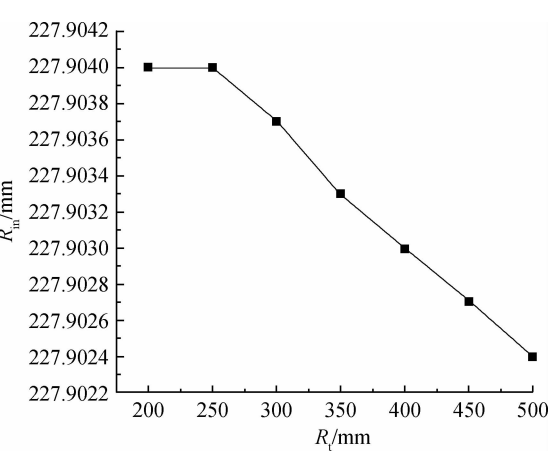


图 16 刀具圆弧半径 R_t 与 R_m 的关系

Fig. 16 Relationship between R_t and R_m

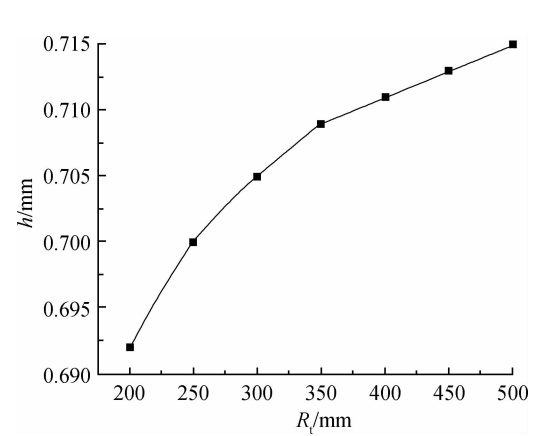


图 17 刀具圆弧半径 R_t 与 h 的关系

Fig. 17 Relationship between R_t and h

3 结 论

本文推导了非正交弧线齿面齿轮齿面方程,并在 Matlab 中得到全齿面的数学模型,从全齿面模型中可看出非正交弧线齿面齿轮内径处发生根

切现象,故以齿面方程为基础结合根切理论求出不产生根切最大内半径,并基于 Catia 二次开发,对非正交弧线齿面齿轮齿坯进行仿真滚齿,进而对所得到的最大内径进行验证。从而在设计之初避免了非正交弧线齿面齿轮齿根发生根切现象。

在同等参数下,探究了位置参数 L_0 和刀具圆弧半径 R_t 对 h 和内径的影响,得出当位置参数 L_0 增大时, h 和内径逐渐减小。当刀具圆弧半径 R_t 增大时,内径逐渐减小, h 逐渐增大。从而得知 L_0 逐渐增大时, h 和内径呈正相关。 R_t 逐渐增大时, h 和内径呈负相关。由于弧线齿面齿轮变量较多,方程较为复杂,该结论亦可辨清非正交弧线齿面齿轮内径与 h 的关系。

参考文献:

[1] LITVIN F L, FUENTES A. Gear geometry and applied theory[M]. New York:Cambrige University Press, 2004.

[2] LITVIN F L, ZHANG Y, WANG J C. Design and geometry of face-gear drives[J]. Journal of Mechanical Design, 1992, 114(4): 642-647.

[3] 李政民卿,朱如鹏. 正交面齿轮齿廓的几何设计和根切研究[J]. 华南理工大学学报(自然科学版), 2008(2): 78-82. LI Zhengminqing, ZHU Rupeng. Investigatio into geometrical design of tooth profile and undercut for orthogonal face-gear[J]. Journal of South China University of Technology (Natural Science Edition), 2008(2): 78-82. (in Chinese)

[4] 朱如鹏,潘升材,高德平. 正交面齿轮传动中齿宽设计的研究[J]. 机械科学与技术, 1999, 18(4): 54-55, 57. ZHU Rupeng, PAN Shengcai, GAO Deping. Study of the design of tooth width of rigaht shaft-angle face-gear drive [J]. Mechanical Science and Technology for Aerospace Engineering, 1999, 18(4): 54-55, 57. (in Chinese)

[5] 王延忠,熊巍,张俐,等. 面齿轮齿面方程及其轮齿接触分析[J]. 机床与液压, 2007, 35(12): 7-9, 47. WANG Yanzhong, XIONG Wei, ZHANG Li, et al. Tooth surface equations and tooth contact analysis of face gear [J]. Machine Tool and Hydraulics, 2007, 35(12): 7-9, 47. (in Chinese)

[6] 彭先龙,郭卫. 面齿轮制造技术综述及未来发展趋势[J]. 制造技术与机床, 2017(9): 36-42. PENG Xianlong, GUO Wei. Research review and development trend of face gear manufacturing[J]. Manufacturing Technology and Machine Tool, 2017(9): 36-42. (in Chinese)

[7] 王延忠,唐文. 基于球形滚刀的面齿轮滚齿加工方法[J]. 北京航空航天大学学报, 2017, 43(3): 441-448. WANG Yanzhong, TANG Wen. Hobbing method of face-gear based on spherical hob[J]. Journal of Beijing University of Aeronautics and Astronautics, 2017, 43(3): 441-448. (in Chinese)

[8] 彭先龙,韩飞燕,乔心州,等.斜齿面齿轮传动齿面主动修形与边缘接触分析[EB/OL]. [2020-05-18]. <http://kns.cnki.net/kcms/detail/11.5946.tp.20190531.0935.002.html>.

[9] 沈云波,方宗德,赵宁.斜齿面齿轮齿宽的设计[J].航空动力学报,2008,23(4):754-758.
SHEN Yunbo,FANG Zongde,ZHAO Ning. The design of tooth face width of the face-gear drives with helical pinion [J]. Journal of Aerospace Power,2008,23(4):754-748. (in Chinese)

[10] 崔艳梅,方宗德,王丽萍.弧线齿面齿轮的根切与变尖研究[J].机械强度,2014,36(4):572-577.
CUI Yanmei,FANG Zongde,WANG Liping. Research on tooth face-gear with undercutting and pointing[J]. Journal of Mechanical Strength,2014,36(4):572-577. (in Chinese)

[11] 崔艳梅,方宗德,王星.考虑安装误差的弧线齿面齿轮承载接触分析[J].机械传动,2015,39(8):115-118.
CUI Yanmei,FANG Zongde,WANG Xing. Load tooth contact analysis for arc tooth face-gear considering assembly misalignment[J]. Journal of Mechanical Transmission,2015,39(8):115-118. (in Chinese)

[12] CUI Yanmei,FANG Zongde,SU Jinzhan. Precise modeling of arc tooth face-gear with transition curve[J]. Chinese Journal of Aeronautics,2013,26(5):1346-1351.

[13] 李清,徐伟俊,张猛.飞刀法加工蜗杆面齿轮的理论研究与实践[J].中国机械工程,2019,30(23):2835-2843.
LI Qing,XU Weijun,ZHANG Meng. Theoretical research and practice of machining worm face-gears by flying cutter method[J]. China Mechanical Engineering,2019,30(23):2835-2843. (in Chinese)

[14] 盛伟,王利霞.弧线齿面齿轮齿面几何设计及径向齿宽特性[J].航空动力学报,2019,34(4):796-803.
SHENG Wei,WANG Lixia. Geometrical design of tooth surface and characteristics of radial tooth width for face-gear with arc tooth[J]. Journal of Aerospace Power,2019,34(4):796-803. (in Chinese)

[15] 张昆仑.非对称弧线圆柱齿轮设计与啮合特性研究[D].西安:长安大学,2017.
ZHANG Kunlun. Study on the design and meshing characteristics of the asymmetric curvilinear cylindrical gears [D]. Xi'an:Chang'an University,2017. (in Chinese)

[16] 苏进展,方宗德.弧线齿圆柱齿轮四阶传动误差设计与分析[J].机械传动,2014,38(9):11-14,19.
SU Jinzhan,FANG Zongde. Design and analysis of fourth order transmission error of circular arc curvilinear of cylindrical gear[J]. Journal of Mechanical Transmission,2014,38(9):11-14,19. (in Chinese)

[17] 常青林,侯力,孙志军.弧齿圆柱齿轮两种加工方法工艺分析[J].机械传动,2014,38(6):96-100.
CHANG Qinglin,HOU Li,SUN Zhijun. Process analysis of two kinds of processing method of cylindrical gear with curvilinear-hape tooth[J]. Journal of Mechanical Transmission,2014,38(6):96-100. (in Chinese)

(编辑:张 雪)