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COLLISION DETECTION BETWEEN TOOLHOLDER AND WORKPIECE ON BALLNUT GRINDING

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Abstract. This paper presents a numerical method for the determination of collision detection of toolholder (quill) and workpiece on ballnut grinding. Beside the collision detection the method is capable of the determination of proper grinding angle with the prescribed safety gap between the toolholder and workpiece. The applied Newton-Raphson and Broyden numerical algorithms were executed with MATLAB computation software.

Keywords: ballscrew, ballnut, grinding, collision, numerical method

1. INTRODUCTION

Gothic-arc profile ballscrew motion transforming mechanisms are widely used in machine tools and the demand for high-lead ballscrews is increasing due to the high-speed manufacturing. The gothic-arc is a symmetrical combined curve of two arcs with equal radius and distance between their centres. These types of ballscrews are manufactured by form grinding, where the grinding tool has corresponding profile [1], ultra-precision ballscrews sometimes lapped after grinding process [2], [3]. In case of long and high lead threaded ballnut the grinding wheel is not tilted at the lead angle of the thread to avoid the collision between the quill and workpiece. *Figure 1* shows the real manufacturing process on conventional thread grinding machine.

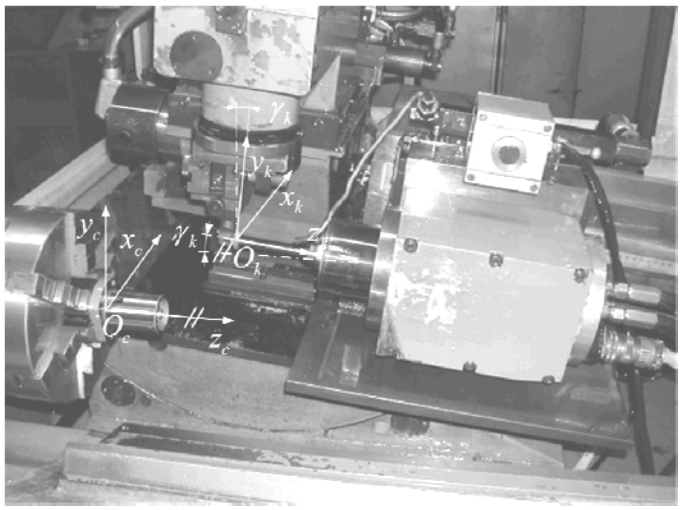


Figure 1. Ballnut thread grinding on conventional machine

Due to these conditions the profile obtained is not gothic-arc, because the grinding wheel tends to overcut the thread surface. The problem is well known in gear and worm manufacturing, different methods had been worked out to solve this task [4], [5], [6]. In case of long threaded ballnut the setting of optimum tilt angle is not possible due to the collision of quill and workpiece. This angle parameter has to be determined for the real manufacturing process. In this paper a numerical method will be presented for the determination of grinding wheel tilt angle on cylindrical and conical toolholders.

2. COLLISION DETECTION BETWEEN QUILL AND BALLNUT

Collision detection between cylindrical bodies is widely used in three dimensional mechanical systems, for example machine tools, robots, different mechanisms. There are different software package for collision detection, for example I-Collide, V-Collide, Rapid, Solid. In this work collision detection is only determined between cylindrical–cylindrical and conical–cylindrical bodies without using of third party developed software.

In case of the ballnut and the quill the determination of collision is equivalent with a minimum distance computation between cylinders or conical and cylindrical surfaces. Detecting of collision between cylindrical rigid bodies were developed using line geometry by Ketchel and Larochelle [8]. Distance computation between cylinders has four different types according to their three dimensional positions in space. Fast and accurate computation method was developed by Vranek [7]. To determine the maximum tilt angle for the grinding the minimum distance determination is required between the tilted quill axis and the edge of the ballnut represented as a circle (see *Figure 2*, where γ_k is tilt angle, φ lead angle – optimal tilt angle – of the ballnut, L_n length of the ballnut, p_h pitch of the ballnut).

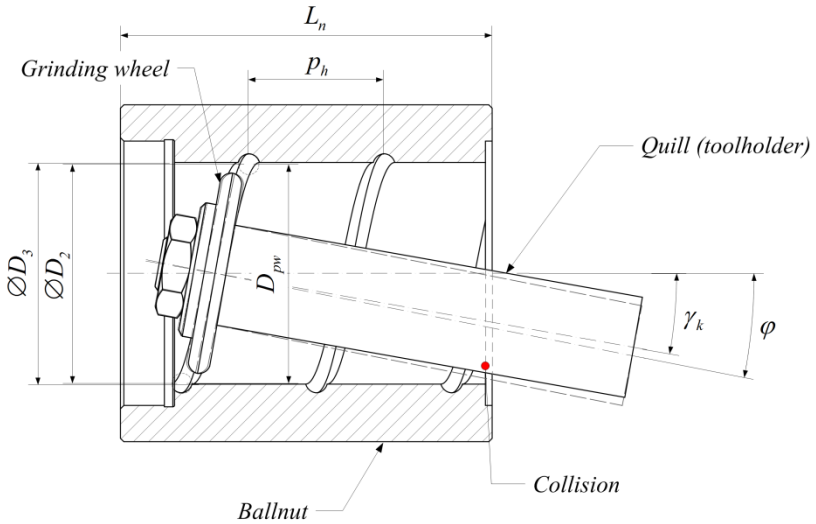


Figure 2. Schematic figure of collision between cylindrical quill and ballnut

2.1. Collision detection between cylindrical quill and ballnut

Determination of minimum distance between the quill and the ballnut is equivalent with the computation of the distance between the quill axis and the circular edge of the ballnut.

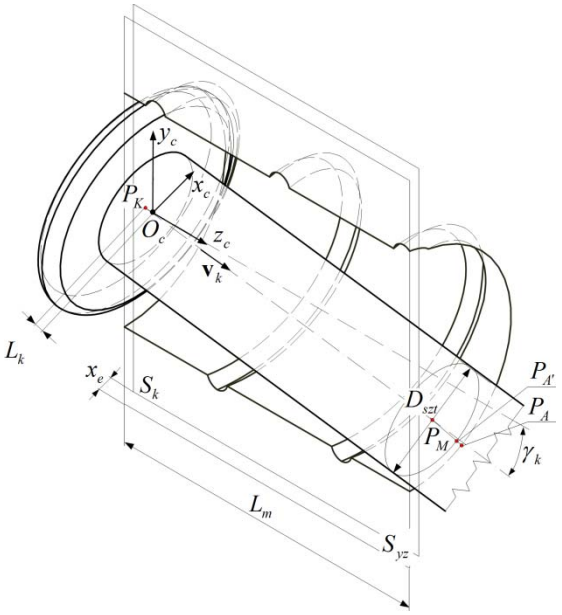


Figure 3. Spatial position of quill-workpiece

Applying notations of *Figure 3* the circle equation described by

$$\mathbf{P}_A = \mathbf{C} + \frac{D_{szt}}{2}\left(\cos(\phi)\mathbf{u} + \sin(\phi)\mathbf{v}\right), \tag{1}$$

where $\phi \in [0, 2\pi]$, $\mathbf{P}_A$ is point of the circle, $\mathbf{C}$ is centre of the circle, D_{szt} is diameter of the quill and $\mathbf{u}$ and $\mathbf{v}$ are unit vectors in the plane containing the circle. The minimum distance between the quill axis and the circular edge is

$$D = \left(\frac{D_{szt}}{2}\right)^2 + \left|\mathbf{C} - \mathbf{P}_M\right|^2 - D_{szt}\frac{\mathbf{Q} - \mathbf{C}}{\left|\mathbf{Q} - \mathbf{C}\right|} \cdot \left(\mathbf{C} - \mathbf{P}_M\right), \tag{2}$$

where $\mathbf{P}_M$ is a point on the quill axis and $\mathbf{Q}$ is the projection of $\mathbf{P}_M$ on the circle plane. Applying the expressions from [9] a nonlinear equation system can be formulated for the unknown parameters. The equation for the minimum distance between the quill and the edge of the ballnut using the notations of *Figure 3* is written by

$$\frac{D_{szt}}{2} + b_h - \left[\left(\frac{D_3}{2}\right)^2 + x_e^2 + \sin^2(\gamma_k)t^2 + \left(L_m + L_k - \cos(\gamma_k)t\right)^2 - D_3\sqrt{x_e^2 + \sin^2(\gamma_k)t^2}\right]^{\frac{1}{2}} = 0, \tag{3}$$

where b_h is a safety gap between the quill and the ballnut, and γ_k is the tilt angle from the $\mathbf{v}_k$ direction vector of the quill axis. Minimizing (2) a quartic equation can be formulated [9]

$$d_4 t^4 + d_3 t^3 + d_2 t^2 + d_1 t + d_0 = 0\,, \tag{4}$$

where

$$\begin{aligned}
d_0 &= \cos^2(\gamma_k)\left(L_k + L_m\right)^2 x_e^2,\\
d_1 &= -2\left(L_k + L_m\right) x_e^2 \cos(\gamma_k),\\
d_2 &= \cos^2(\gamma_k)\left(L_k + L_m\right)^2 + x_e^2 - \left(\frac{D_3}{2}\right)^2 + 2\cos^2(\gamma_k)\left(\frac{D_3}{2}\right)^2 -\\
&-\cos^4(\gamma_k)\cdot\left(L_k + L_m\right)^2 - \cos^4(\gamma_k)\left(\frac{D_3}{2}\right)^2,\\
d_3 &= -2\left(L_k + L_m\right)\cos(\gamma_k)\sin^2(\gamma_k),\\
d_4 &= \sin^2(\gamma_k).
\end{aligned} \tag{5}$$

The roots of the nonlinear equation system from (3) and (4) are found by root finder algorithm. In this work *Newton-Raphson* and *Broyden* numerical algorithms are used for the solving of the nonlinear equation system and the results are compared. Initial values are required for the two unknown parameters on both methods. *Figure 4* shows the quill and the workpiece position for initial value determination.

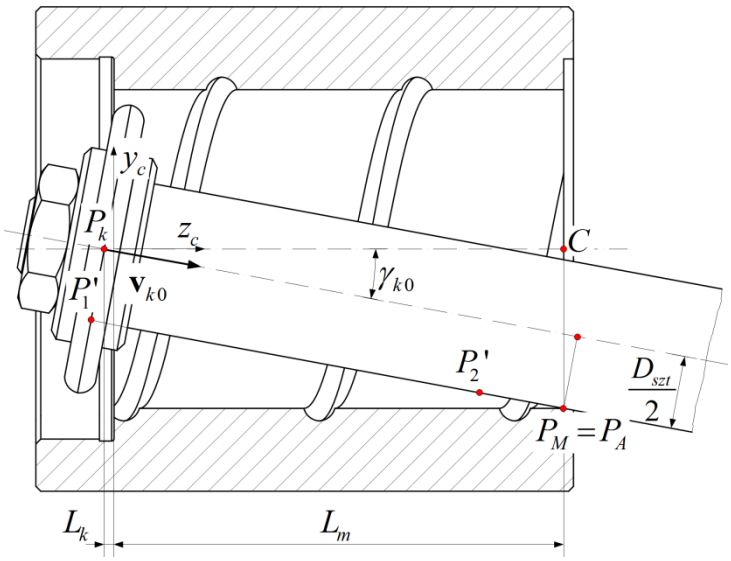


Figure 4. Quill and workpiece position for initial value determination on cylindrical quill

Assuming that the quill and the ballnut axes are in the same $y_c z_c$ plane. The initial γ_{k0} tilt angle and the initial t_0 quill axis parameter are determined by

$$\frac{\left|\left(\mathbf{P}_A-\mathbf{P}_1'\right)\times\left(\mathbf{P}_A-\mathbf{P}_2'\right)\right|}{\left|\mathbf{P}_2-\mathbf{P}_1\right|}=0\,, \tag{6}$$

where

$$\mathbf{P}_i'=\begin{bmatrix}1 & 0 & 0\\ 0 & \cos\left(\gamma_{k0}\right) & -\sin\left(\gamma_{k0}\right)\\ 0 & \sin\left(\gamma_{k0}\right) & \cos\left(\gamma_{k0}\right)\end{bmatrix}\cdot\mathbf{P}_i,\ \left(i=1,2\right) \tag{7}$$

applying the *Figure 4* notations. Solving equation (6) the required initial values for the iterative algorithms are

$$\gamma_{k0}=-2\cdot\arctan\left(\frac{2\cdot\left(L_k+L_m\right)-\sqrt{D_3^2+4\cdot\left(L_k+L_m\right)^2-D_{szt}^2}}{D_3+D_{szt}}\right),$$
$$t_0=L_k\cos\left(\gamma_{k0}\right)+\sqrt{L_k^2\cos^2\left(\gamma_{k0}\right)+\left(\frac{D_3}{2}\right)^2+\left(L_m+L_k\right)^2-D_{szt}^2}\,. \tag{8}$$

2.2. Collision detection between conical quill and ballnut

In the previous section the equation system was formulated for the determination of the tilt angle of the quill, where the quill was cylindrical. In certain cases conical quills are used in grinding process. The determination of the conical quill tilt angle is similar to the cylindrical case, but equation (3) has to be modified according to the taper angle of the quill (see *Figure 5*).

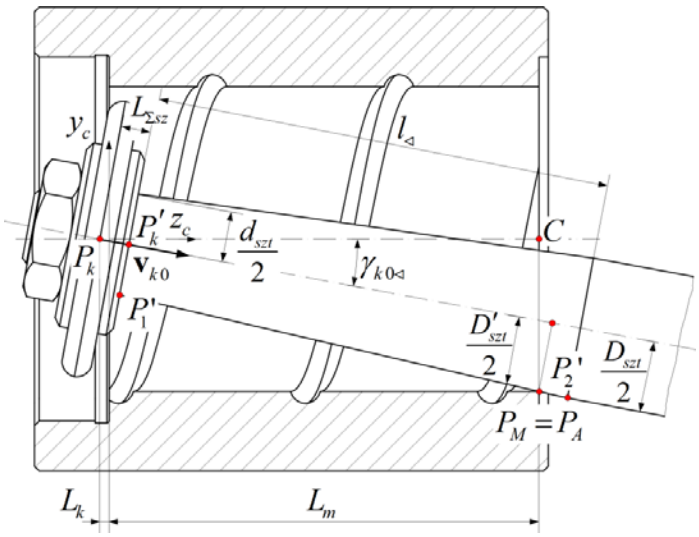


Figure 5. Quill and workpiece position for initial value determination on conical quill

The modified expression is

$$\left[\frac{d_{szt}}{2}+\sqrt{\sin^2(\gamma_k)t^2+\left(\cos(\gamma_k)t-\frac{b_{sz}}{2}-b_j\right)^2}\tan(\kappa)+b_h\right]- \\ -\left[\left(\frac{D_3}{2}\right)^2+x_e^2+\sin^2(\gamma_k)t^2+\left(L_m+L_k-\cos(\gamma_k)t\right)^2-D_3\sqrt{x_e^2+\sin^2(\gamma_k)t^2}\right]^{\frac{1}{2}}=0, \tag{9}$$

where d_{szt} is the smaller diameter of the quill, b_{sz} is the grinding wheel width and b_j is the width of additional parts. Solving equation (6) similarly the initial values are,

$$\gamma_{k0\triangleleft}=2\arctan\left(\frac{4l_\triangleleft(L_k+L_m)-D_3d_{szt}-a+D_3D_{szt}}{2\left(D_{szt}\left(b_j+\frac{b_{sz}}{2}+(L_k+L_m)\right)-l_\triangleleft(D_3+d_{szt})-d_{szt}\left(L_k+L_m+b_j+\frac{b_{sz}}{2}\right)\right)}\right),$$

$$a=\left[4\left((D_{szt}-d_{szt})^2+l_\triangleleft^2\right)(L_k+L_m)^2+D_3^2\left((D_{szt}-d_{szt})^2+4l_\triangleleft^2\right)+D_{szt}^2\left(4b_jb_{sz}-4b_j^2+b_{sz}^2\right)-\right. \\ \left.-d_{szt}^2\left(4b_j(L_{\Sigma sz}+2l_\triangleleft)+b_{sz}^2+4l_\triangleleft(b_{sz}+l_\triangleleft)\right)+2D_{szt}b_{sz}d_{szt}(b_{sz}+2l_\triangleleft)+8D_{szt}b_jd_{szt}(L_{\Sigma sz}+l_\triangleleft)\right]^{\frac{1}{2}}, \tag{10}$$

$$t_{0\triangleleft}=L_k\cos(\gamma_{k0\triangleleft})+\sqrt{L_k^2\cos^2(\gamma_{k0\triangleleft})+\left(\frac{D_3}{2}\right)^2+(L_m+L_k)^2-D_{szt}'^2},$$

$$D_{szt}'=\frac{2\left|(\mathbf{P}_A-\mathbf{P}_k)\times(\mathbf{P}_A-\mathbf{v}_{k0})\right|}{\left|\mathbf{v}_{k0}\right|},$$

where $\mathbf{P}_1=[0,\ d_{szt}/2,\ L_{\Sigma sz}]$ and $\mathbf{P}_1=[0,\ D_{szt}/2,\ L_{\Sigma sz}+l_\triangleleft]$ (see *Figure 5*).

3. DETERMINATION OF QUILL TILT ANGLE

In the previous section the collision detection has been described to cylindrical and conical quill by a quartic nonlinear equation system. There are different root finding methods for solving nonlinear equation [10]. In this work the Newton-Raphson and Broyden methods have been applied to solve the equation systems (numerical computations made by MATLAB software). Tab. 1. shows the computed tilt angles when the initial guesses were zeros, where i is the iteration number and ε is the absolute relative approximate error. The predefined tolerance for the absolute relative error was $\varepsilon=10^{-6}$, the run-out of the tool was L_k=1mm (see *Figure 3*) and the safety gap between the quill and workpiece was b_h=1mm on both numerical methods.

Table 1

Computed tilt angles at $\gamma_{k0}=0$ and $t_0=0$

Dimension	**Numerical algorithm**	γ_k [°]	i	ε [°]
32 x 25	Newton-Raphson	$-4{,}788076\cdot10^{5}$	11	$1{,}016858\cdot10^{-9}$
	Broyden	$-1{,}853271\cdot10^{6}$	51	$1{,}426114\cdot10^{-8}$
40 x 20	Newton-Raphson	$-5{,}180525\cdot10^{5}$	15	$3{,}731273\cdot10^{-9}$
	Broyden	$3{,}487852\cdot10^{6}$	139	$9{,}544611\cdot10^{-9}$
40 x 30	Newton-Raphson	$-5{,}158853\cdot10^{5}$	14	$6{,}711693\cdot10^{-7}$
	Broyden	$-1{,}789745\cdot10^{6}$	148	$1{,}672484\cdot10^{-7}$
50 x 30	Newton-Raphson	$-4{,}989719\cdot10^{5}$	5	$2{,}159759\cdot10^{-9}$
	Broyden	$-4{,}989480\cdot10^{5}$	22	$2{,}856460\cdot10^{-8}$

Table 2

Computed tilt angle at predefined γ_{k0} and t_0

Dimension	**Numerical algorithm**	t_0 [mm] γ_{k0} [°]	γ_k [°]	i	ε [°]
32 x 25	Newton-Raphson	63,169352 10,135615	7,653505	5	$7{,}151210\cdot10^{-8}$
	Broyden		7,653505	8	$2{,}708951\cdot10^{-8}$
40 x 20	Newton-Raphson	93,147753 8,481599	6,952097	5	$4{,}675239\cdot10^{-7}$
	Broyden		6,952097	7	$4{,}859574\cdot10^{-8}$
40 x 30	Newton-Raphson	102,8418 7,180805	5,260079	5	$7{,}800237\cdot10^{-8}$
	Broyden		5,260079	8	$8{,}030855\cdot10^{-9}$
50 x 30	Newton-Raphson	136,217801 7,196824	5,651421	5	$3{,}449851\cdot10^{-9}$
	Broyden		5,651421	7	$6{,}958383\cdot10^{-9}$

Applying the predefined initial guesses on the Newton-Raphson and Broyden methods the computed quill tilt angle becomes more accurate and number of the iterations is decreased (see Tab. 2.). Computations have been carried out to conical and cylindrical quill as well. In order to control accuracy and reliability of the results a graphical user interface has been developed under MATLAB.

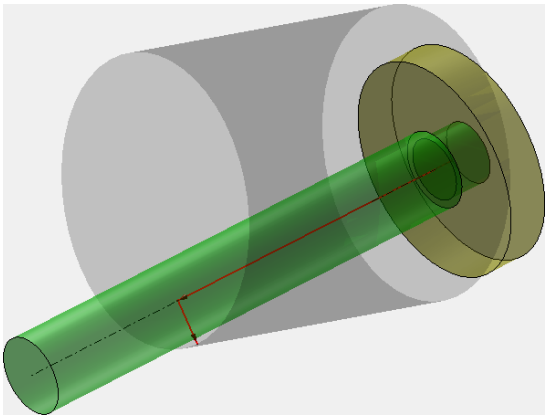


Figure 6. Visual control of computed result

Figure 6 shows result of a ballnut with 50x30 dimensions, where the safety gap between the cylindrical quill and workpiece was 1mm. The ballnut was substituted by a cylinder according to its smallest diameter (gray cylinder on *Figure 6*).
In order to control the collision on the real ballnut and quill surface further future work would be carried out. There are to method for this purpose, one of them to develop the described algorithm under the proper CAD system in which the ballnut and quill are modelled. Other ways to prepare the ballnut's CAD model in system neutral file format (e.g. STL format) and visualized in the MATLAB graphical user interface.

4. CONCLUSION

This paper presents a numerical method on the collision detection between workpiece and quill. The quill tilt angle is an important manufacturing parameter on ballnut grinding. The Newton-Raphson and Broyden methods were analysed with different initial guesses. One of the disadvantages of iteration algorithms has pointed out, namely inadequate initial guess raises the iteration's number and results inappropriate solutions. Results have become correct, number of iterations have been decreased with predefined initial guesses.

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