Investigation of the influence of the cutter-tool rake angle on the accuracy of the conical helix in the tapered thread machining

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Abstract. Tapered thread joints used in drill pipes largely determine the productivity of drilling processes and their environmental reliability. The quality of these joints depends on the values of the rake angle of the cutting insert of turning cutters used for making tapered threads. Modern manufacturers, because of the absence of algorithms for calculating the precision of the execution of the tapered thread spiral, depending on the size of the rake angle use the cutters only with a zero value of this angle. This greatly limits the possibility of producing drill pipes from high-strength materials, which is absolutely necessary in the modern drilling methods: obliquely directional and horizontal. The kinematic analysis presented in the article proves the difference between the theoretically specified spiral and their realized in the course of machine processing with cut tools with non-zero values of the rake angle. The deviation of the thread incline angle that is realized during turning is not regulated by standard requirement, as it is variable. The precision of the pitch of the tool-joint tapered thread is regulated by standard and must be ensured by the kinematics of the lathe. However, when screwing, the spiral screw lines of the pin and the box thread may not match, provided that they are made with using of tools with different values of the rake angle. Thus, it is lead to exceed the tolerances by one pitch. The algorithm allows to calculate the axial deviations of the screw line, depending on the value of the rake angle of the cutter for any of the points of the thread profile. It brings the fit of the cutters with a rake angle up to 5° to ensure the accuracy of the executed helices in the tapered thread machining.

1. Relevance of the problem
The process of modern drilling needs the large improvement of the drilling equipment designs, tools, and manufacturing technologies. Drilling tools include drill bits, pipes, adapters, etc. Design [1], [2], technological [3], [4], and operational methods [5-7] are used to increase drilling tool durability. Drilling tool-rock interaction is simulated [8-10] to substantiate drilling modes taking into account thermal effects [11], [12]. It should be noted that drill pipes are the most widely used drilling tools comparing to other drilling equipment. The most complex and responsible part of the drill pipe is the tool joint for drill pipes – the connector of pipes and other elements of the drill string. It is intended for mechanical fastening of drill pipes among themselves and for ensuring tightness. Both of these requirements largely depend on the accuracy of the tapered thread on both parts of the drill-string tool.
joint – pin and box [13]. Since tapered threads are produced by means of machining on lathes, the accuracy thus largely depends on the accuracy of lathe threading machine tool and cutters.

Therefore, the comprehensive identification of problems of precision cutting, which arise in the process of thread manufacturing is associated with both theoretical studies of the kinematics of lathes and with studies of the impact of the obtained precision of the thread on its operation parameters.

2. Analytical and experimental study of the kinematics of the tapered thread machining by lathe

The investigation of the accuracy of the tapered thread depending on the profile of the cutting edge of the lathe tools is shown in the work [14]. Analytical investigations of mechanical static tensions in connectors of the oil and gas pipe assortment depending on the accuracy of the thread profile are shown in the articles [2], [13], [15]. The dynamics of the chip formation process during threading by lathe is considered in the paper [16]. The parametric model of the cutting process whose parameters are the kinematic geometric parameters of the cutter is offered in work [16]. Paper [17] shows the dependence of the process of cutting hard-machining steels, depending on the static and kinematic geometric parameters, in particular, the rake angle of the cutter. The article [18] deals with modelling of the wear resistance of the cutter depending on the change of cutting force in the turning process. The experimental investigations of the cutting process using work pieces from hard-machining high-alloy chromium steels are carefully considered in the work [19]. In [20], the results of researches of the vortex turning kinematics of cylindrical thread have been offered. The researches of the accuracy of the cylindrical thread obtained by applying the cutting process are shown in [21]. Of all these reports the work [22] is the closest to the subject of the article. Experiments of a design are shown in paper [22]. The geometry in multi-point thread turning is studied in [23]. Stress analysis on the thread teeth are shown in [24]. The influence of the profile and geometrical parameters of the tool bit cutting edge on the contact pressures and tightness of the threaded drill-string connection have been investigated in the works [25], [26]. The loading analysis on the thread teeth in cylindrical pipe thread connection are studied in paper [27]. The study of the influence of the accuracy of the thread surface on the contact pressures is considered in the work [28].

Methodologically that study relies on the theory of circular vector functions [29]. According to this theory, the radius vector \( \vec{r} \) describes the movement of an arbitrary point \( M \) along a helical curve with a constant pitch on the tapered surface using this equation [30] (look at Figure 1):

\[
\vec{r} = a(\theta) \cdot \vec{e}(\theta) + \frac{k \rho \theta}{2\pi},
\]

where:
P – thread pitch,
\( \theta \) – value of the rotate angle arbitrary point \( M \) relatively thread axis,
\( a(\upsilon) \) – value of the tapered radius at arbitrary point \( M \),
\( \vec{e}(\upsilon) \) – two unit vectors situated relatively axis 0X form angles \( \upsilon \) and \( \upsilon + 90^\circ \).

The circular vector function \( \vec{g}(\theta) \) can be expressed as follows [26], [27]:

\[
\vec{g}(\theta) = \vec{e}(\theta + \frac{\pi}{2}).
\]

On the other hand, since this vector lies on the tangent line to the circuit in which the vector \( \vec{e}(\theta) \) is placed radially, then [26], [27]:

\[
\vec{g}(\theta) = \frac{\partial \vec{e}}{\partial \theta}.
\]
The differential equation that defines the derivative of the position vector \( \dot{r} \) with respect to its rotate angle \( \nu \) around the axis \( Ox \) is offered in article [27]:

\[
\frac{d\dot{r}}{d\theta} = \left( \frac{ptg(\varphi)}{2\pi} \right) \cdot \vec{e}(\theta) + \left( P \cdot t\varphi(\varphi) - \frac{\varphi}{2} + \left( \frac{d_s}{2} - \Delta \right) \cdot \vec{g}(\theta) + \frac{k}{\sqrt{r}} \cdot P / 2\pi \right).
\]

On the figure 1 the vector \( \vec{S} \) (between points 2 and 3) corresponds the first addendum of the formula 2, the vector \( \vec{G} \) (between points \( M \) and 1) corresponds the second addendum of the same equation and the vector \( \vec{K} \) (between points 1 and 2) corresponds the third addendum of the formula. So the equation (2) takes this form:

\[
\frac{d\dot{r}}{d\theta} = \vec{V}_r = \vec{S} + \vec{G} + \vec{K}.
\]

Vector \( \vec{V}_r \) is tangent line to helical curve at a point \( M \) but it isn’t correspond summary speed of its motion because its value is defined as a change of the position vector long with respect to a change in rotate angle \( \nu \) around the axis of the thread. So:

– equation 2 does not describe the speed of the motion of the point \( M \);

– because the vector \( \vec{S} \) in formula 3 lies individually for every arbitrary point on the helical curve it is impossible to provide it by the machine tool.

3. Theoretical determining of the angle of inclination of a conical helix with a constant pitch

Based on equations (1) - (3) and using Figure 1 determine the radial, tangential and axial components of the vector of the direction of the resulting motion \( \vec{V}(\theta) \) of an arbitrary point of a conical helix.

The length of the radial component of the vector \( \vec{V}(\theta) \) depending on the choice of the beginning of the movement from the larger or smaller base of the truncated cone is determined by the equation

\[
|\vec{V}_r| = |\pm p \cdot t\varphi(\beta)|.
\]

The length of the tangential component of the vector of the direction of movement can be calculated by the equation

\[
|\vec{V}| = R - p\theta t\varphi(\beta).
\]
or

\[ |\vec{V}| = r \pm p\vartheta \tan(\beta). \quad (5) \]

The length of the axial component of the vector of the direction of movement is calculated by the formula

\[ |\vec{V}_0| = \pm p. \quad (6) \]

In Figure 1 the angle \( \Theta \) – the angle of inclination of the tangent to the helical line at an arbitrary point \( M \) is showed. The specified tangent is determined by the vector \( \vec{V}(\vartheta) \). The angle \( \Theta \) lies in the \( DMA \) plane and can be determined by the formula

\[ \theta = \arctg \frac{\vec{V}_1}{|M 1|}. \quad (7) \]

Using Figure 1, and applying the Pythagorean theorem we obtain the following:

\[ |M 1| = \sqrt{|\vec{V}|^2 + |\vec{V}_r|^2}. \quad (8) \]

Substituting formula (7) in equation (8) and given that \( \vec{V}_0 = \overrightarrow{AD} \) we obtain:

\[ \theta = \arctg \frac{|\vec{V}_0|}{\sqrt{|\vec{V}|^2 + |\vec{V}_r|^2}} \]

therefore:

\[ \theta = \arctg \frac{p}{\sqrt{(r + p\vartheta \tan(\beta))^2 + (p\vartheta \tan(\beta))^2}}. \]

Because according to the expressions: \( \vartheta = \frac{h}{p} \) and \( p = \frac{P}{2\pi} \), then after substituting these expressions into the equation (9):

\[ \theta = \arctg \frac{p}{\sqrt{(p\vartheta \tan(\beta))^2 + \pi^2(2r + 2h \cdot \vartheta \tan(\beta))^2}}. \quad (9) \]

4. Determining the inclination angle of the tapered thread with a constant pitch

The efficiency of the cutting process depends on the magnitude of the static rake angle \( \gamma_a \) at the corner of the cutter as well as the rake angles at other points of the cutting edge. The nominal value of the rake angle at an arbitrary point \( M \) of the cutting edge of the threading cutter can be determined using Figure 2 by equation:

\[ \gamma_m = \arcsin \left( \frac{r_m}{r_a} \sin(180^\circ - \gamma_a) \right), \quad (10) \]

where: \( r_m \) – the radius for the point \( M \) is determined by the formula

\[ r_m = r_c - \Delta = \frac{d_2}{z} + Pt gp \cdot \frac{\vartheta}{2\pi} + b - \Delta. \quad (11) \]

\( r_a \) – the radius for point \( A \) is determined by the formula:

\[ r_a = \frac{d_2}{z} + Pt gp \cdot \frac{\vartheta}{2\pi} + b + f - H. \]
Figure 2. Scheme for determining the parameters of placement of an arbitrary point of the cutting edge of the cutter for turning a tapered thread. The symbols indicate: \( d_3 \) – outer diameter of the tapered thread on the side of the smaller base; \( b \) – section of the top of the thread; \( f \) is the cut of the cavity of the cut; \( m_1 \) and \( m' \) are vertical and horizontal projections of the point \( M \); \( \Delta \) is the radial distance of an arbitrary point \( m_1 \) of the cutting edge from the outer vertex of the output triangle; \( \Delta_1 \) is the difference of radial distances between the vertex and arbitrary point of the cutting

Taking into account formula (1) and substituting equation (11) in it, we have the equation of the radius vector

\[
\vec{r}_M = \left( \frac{d_3}{2} + Pt g \phi \cdot \frac{\theta}{2\pi} - \Delta + b \right) \cdot \vec{e}(\theta) + \vec{v} p \theta.
\]

After the derivative of the function radius-vector with respect to time \( t \) the equation of the speed of point \( M \) (arbitrary point of the cutting edge) will be obtained

\[
\frac{d\vec{r}_M}{dt} = 2\pi n \left[ \left( Pt g(\phi) \frac{\theta}{2\pi} \right) \vec{e}(\theta) + \left( P \cdot t g(\phi) \frac{\theta}{2\pi} + \left( \frac{d_3}{2} - \Delta + b \right) \right) \vec{g}(\theta) + \vec{k} \frac{P}{2\pi} \right].
\]

Therefore, the determination of the speed of movement of an arbitrary point on a helical line with a constant pitch on a conical surface (12) can be represented as follows:

\[
\frac{d\vec{v}_M}{dt} = \left| \vec{S}_m \right| \cdot \vec{e}(\theta) + \left| \vec{v}_m \right| \cdot \vec{g}(\theta) + \left| \vec{F}_a \right| \cdot \vec{k}.
\]

The constituent vectors of this expression are determined by formulas:

\[
\vec{S}_m = (Pt g(\phi) n) \cdot \vec{e}(\theta),
\]

\[
\vec{v}_m = 2\pi n \left( P \cdot t g(\phi) n \cdot t + \left( \frac{d_3}{2} - \Delta + b \right) \right) \cdot \vec{g}(\theta),
\]

\[
\vec{F}_a = \vec{k} P n.
\]

However, the machine tool is not able to provide the vector \( \vec{S}_m \). It can do only transverse motion with speed \( \vec{F}_a \) - the same for every points.
Figure 3. Layout of vectors of velocity of the resulting motion \( \vec{V}_e \), main motion \( \vec{V}_m \), velocities: longitudinal \( \vec{F}_a \) and transverse feed \( \vec{F}_t \).

The real inclination angle of the tapered thread \( \theta_p \) can be calculated based on Figure 3 by the formula:

\[
\theta_p = \arctg \left( \frac{|\vec{F}_a|}{|\vec{V}_m|} \right)
\] (13)

Therefore, based on equation (13), the real inclination angle of the tapered thread should be calculated by the formula:

\[
\theta_p = \arctg \left( \frac{p_n}{\sqrt{(|\vec{V}_m'|-ptg(\phi)n\sin(\gamma_a-\gamma_m))^2 + (ptg(\phi)n\cos(\gamma_a-\gamma_m))^2}} \right).
\]

5. Conclusions
1. Studies have shown the difference between the theoretical angle of elevation of the conical helix and by the angle of elevation of the thread, which can be implemented on a lathe.
2. The helix angle of the tapered thread depends on the value of the rake angle of the cutting tool.
In further studies, it is planned to consider the influence of the rake angle on the pitch accuracy of the tapered thread.

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