Standardization and control of thread parameters of a roller-screw gear

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Abstract. Among the mechanisms that transform rotational motion into translational motion, helical gears of rolling, which provide higher efficiency and speed, are currently dominant. These include ball-screw gears and roller-screw gears. A comparative analysis of these showed that the latter has a number of limitations compared to the former. Serial production requires the development of automated technologies for machining, assembly and testing, the use of high-precision metrological equipment to control functional surfaces with minimal time costs in digital automated systems. Modern measuring instruments, such as contour meters allow for element-by-element control of the parameters of threaded surfaces. In the manufacture of high-tech products such as an electromechanical drive, the use of element-wise control is the only way to ensure product quality. However, not enough standardization of the parameters of the thread of the roller-screw gears requires the development of a set of requirements that provide the specified operational characteristics of the product. The work is devoted to the standardization of the parameters of the special roller-screw gears thread used in the electromechanical drive manufactured by AO Diakont. This article discusses issues related to the standardization of the accuracy parameters of the profiles of high-precision roller-screw gears, metrological support tools, a set of techniques and software based on a systematic approach to inputting, outputting and transmitting information about measurement results and evaluating their validity. The application of the proposed control methodology allowed improving the quality of products and reducing its cost.

1. Introduction
The development of computer technologies used in manufacturing management systems leads to the emergence of new requirements for the functioning of these systems. One of the promising areas is the use of electromechanical drives (EMD) as part of control systems for synchronous motors. This type of drive has found application in the automotive industry, aerospace, steam turbine control systems and many other industries [1-2]. The use of modern technologies of mechanical and heat treatment of parts of a roller-screw transmission can improve the operational characteristics of the product [3-5]. The control of the special internal thread of the roller-screw drive is a complex technological and metrological task. At the moment, there is no generally available international or national standard for threading a roller-screw drive. The closest standards are GOST 11708-82 [6] and ISO 3408-1: 2006 [7]; however, they do not cover all the parameters necessary to ensure the operation of the gear. In [8], an
analysis was made of the methods for measuring the parameters of the internal thread; however, none of them provides control of the full range of requirements for the thread of a roller-screw gear.

2. Terms and definitions

Based on the functional purpose for describing the profile of threaded surfaces, it is proposed to use the following definitions.

*Contour of the threaded surface of a roller-screw gear* is the identified profile of the threaded surface of the roller-screw gear in axial section, obtained as a result of one measuring pass of the contour meter described by an array of points with coordinates xi, yi.

*Turn* is a section of a thread contour related to one full revolution of the points of the helical line of the thread relative to the axis.

*Thread generator* (O1, O2) is a segment of the contour of the threaded surface connecting the top and bottom of the thread.

*Top of the thread* (A1, A2) is a segment of the contour of the threaded surface connecting the generators of adjacent turns along the top of its protrusion.

*Bottom of the thread* (V) is a segment of the contour of the threaded surface connecting the generatrixes belonging to one thread along the bottom of its groove.

*Inscribed circle* is a circle of a given diameter dc, tangent to the generators of one thread at two points with centers described by the coordinates Xi, Yi.

*Screw pitch* (SP) is the distance between the centers of adjacent inscribed circles of one contour.

*Average diameter of the thread* (D2) is the distance between the centers of the nearest inscribed circles for opposite thread contours.

*Scan length* is the stroke length of the contour meter.

*Controlled length* (Lu) is the length of the identified thread profile after exclusion of incomplete turns.

*Roller length* (LR) is a segment of geometric length in contact with the mating surface.

*Actual interval of variation of the average diameter over the entire controlled length* (OD2) is the difference between the largest and smallest values of the average diameter of the thread over the entire controlled length.

*Actual interval of variation of the average diameter on the length of the roller* (OD2R) is the difference between the largest and smallest values of the average diameter of the thread along the length of the roller.

*Actual translation* is the actual Y coordinate of the center of the inscribed circle.

*Actual mean translation* is a straight line plotted through the values of the actual displacement by the method of least squares.

*Actual value of the error of the average translation within the measurement length* (Ea) is the difference between the actual average translation on the measurement length and the nominal movement for a given length.

*Actual interval of the error of the average translation within the measurement length* (Vua) is the value of the interval of the accumulated error of steps within the measurement length.

*Tolerance of a given thread profile* is the distance along the normal to the nominal thread profile from the nominal thread profile to the controlled point of the identified thread profile.

3. Determining identified profile

In view of the foregoing, Figure 1 shows a diagram for determining the identified thread contour using a Mitutoyo SV-C4500 contour meter:

- Point 0 – the starting point of the control program;
- Point 1 – start of measurement of the contour CI;
- Point 2 – end of the measurement of contour CI, change of direction of the measuring force
- Point 3 – start of measurement of the contour C2;
- Point 4 – end of contour measurement C2;
Point 0 – change of direction of the measuring force, completion of the control program. The figure shows the following coordinate axes used in the measurement:

- Z1 – axis of the column of the contour meter
- Z2 – axis of the probe
- X – longitudinal axis of the contour meter
- x, y – part coordinate system

![Diagram of thread profile scanning](image)

**Figure 1.** Scheme of thread profile scanning

The part is mounted on the contour meter, ensuring that the axis of symmetry of the part is located on the coordinate plane XZ1 of the contour meter. The measuring probe is brought to point 0 in the position Z2 = 0, the probe is lowered until the measuring tip contacts the surface of the part at point 1, after which the circuit $C_1$ is scanned. At the endpoint 2 of circuit $C_1$, the direction of the measuring force is changed, the probe touches the surface of the part at point 3, the measurement of the circuit $C_2$ begins, the measurement of the circuit ends at point 4, after which the probe is taken to the starting point and the direction of the measuring force is changed. Scan results are saved on the server as a text file with .dat extension.

The file with the coordinates of the profile points contains the following information: the units of measurement used (usually mm) are recorded on the first line of the file, the number of points making up one thread contour from the start to the end point of the scan is indicated on the second line, and the coordinates $x_i$, $y_i$ of every point are written in the following lines. If there are several loops in the same file, after the last point of the first loop, information on the remaining loops is similarly recorded. Each measured circuit contains up to 10,000 points.

After reading points from the file into the data.point table, each point is assigned the name of the contour to which it refers. Each contour is divided into intervals with a length equal to the thread pitch. Each turn is divided into five segments: A1, O1, V, O2, A2. The scheme for dividing a thread into segments is shown in Figure 2. Section V is defined as points having a y coordinate less than $y_V$ specified in the nominal thread data.
Figure 2. Dividing thread turn profile into segments

Figure 3. Determining the boundary of the segments $O_j, A_j$
The definition of the segments $A_1$, $O_1$ and $A_2$, $O_2$ is shown in Figure 3. The points that are guaranteed to belong to these segments are preliminarily selected. Points located to the left of the $-x$ coordinate of the part specified in the nominal data are accepted as segment $A_1$, those located to the right, are accepted as segment $O_1$. After that, for each section, the equation of the line is calculated using the least squares method; the coordinates of the intersection of these lines are found. This point is taken as the border of two segments, the points located to the left of the border belong to the segment $A_1$, those to the right, belong to the segment $O_1$. Plots $A_2$, $O_2$ are determined symmetrically.

4. Calculating the centers of the inscribed circles
The coordinates of the center of the inscribed circle $X_0$, $Y_0$ of a given radius are calculated for several iterations for each thread turn. For the first one, the average coordinates of the profile points are taken as the center coordinate.

$$X_0 = \frac{\sum_{i=m}^{n} x_i}{n-m}; \quad Y_0 = \frac{\sum_{i=m}^{n} y_i}{n-m},$$

where $m$ is the minimum point number related to this turn, $n$ is the maximum point number related to this turn.

After that, the gap $e_1$, $e_2$ between the inscribed circle and the revealed thread profile is calculated by the following equation:

$$e_1; e_2 = \sqrt{\min((X_0 - x_i)^2 + (Y_0 - y_i)^2)} - d_c$$

$$e = \min(e_1, e_2)$$

After calculating the size of the gap, the coordinates of the center are recalculated by the following equation:

$$X_0 = X_0 + e \cdot \sin \alpha$$
$$Y_0 = Y_0 - e \cdot \sin \alpha,$$

where $\alpha$ is the half of the thread profile angle in axial section.

When the value of $e \leq 10^{-10}$ is reached, the circle is considered inscribed, and the values $X_0$, $Y_0$ are entered in the data center table as $X_i$, $Y_i$, where $i$ is the current thread turn number.

Figure 4. Calculation of the center of the inscribed circle
5. Assessment of the geometric parameters of the thread

5.1. Thread pitch estimation

For each thread turn within the contour, the actual values of the thread pitch are calculated according to the following equation:

\[ SP_i = X_{i+1} - X_i, \]

where \( SP_i \) is the actual value of the \( i \)-th thread pitch on the lower/upper detected contour, \( X_i, X_{i+1} \) are the coordinates along the abscissa of the centers of the inscribed circles that are calculated separately for the contour \( C_1 \) and \( C_2 \).

For each turn, the value of the accumulated error of the thread pitch is calculated using the following equation:

\[ CSP_i = CSP_{i-1} + (SP_i - SP_{\text{nom}}), \]

where \( CSP_i, CSP_{i-1} \) is the accumulated error on the \( i \)-th and the preceding thread pitches, respectively, on the lower/upper detected contour within the measurement length, \( SP_{\text{nom}} \) is the nominal value of a thread pitch according to the design documentation.

Having determined the pitch values, we can calculate the accumulated pitch error. To do this, according to the obtained values of \( SP_i \) by the least squares method, the dependence \( CSP(X) \) of the trend line for the accumulated error is determined:

\[ Ea = k \cdot X, \]

where \( Ea \) are the errors of average displacement within the measurement length, \( k \) is the tangent of the line slope of the actual average translation.

For the resulting equation, the maximum positive \( r_1 \) and negative \( r_2 \) error are calculated:

\[ r_1 = |\min(CSP_i - k \cdot x_i)| \]

\[ r_2 = |\max(CSP_i - k \cdot x_i)|. \]

Then the value of the error interval of the average translation within the measurement length (\( V_{uaa} \)) is calculated by the following equation:

\[ V_{uaa} = r_1 + r_2. \]

Figure 5. Calculation of the parameters of the accumulated pitch error

5.2. Estimating average thread diameter

The calculation of the average diameter of the thread mimics a three-wire measurement scheme used to control the external thread. Figure 6 illustrates the calculation of the average diameter. The calculation of the average diameter for one inscribed circle of the lower contour involves three inscribed circles for the upper contour, this calculation scheme is adopted based on the characteristics of a multistart thread. For each thread, we calculate the value of the average diameter:
where \( Y_{c1} \) are the coordinates of the centers of the inscribed circles for the contour \( C_1 \), \( Y_{c2} \) are the coordinates of the centers of the inscribed circles for the contour \( C_2 \).

To exclude the influence of fluctuations in the \( Y \) coordinate of adjacent inscribed circles on the value of \( D_2 \) and to increase the stability of the result, the filtering procedure for the obtained values is performed according to the following equations:

\[
D_2^i = \frac{D_{2i-1} + D_{2i+1}}{2} \\
D_2^n = \frac{0.5 \cdot D_{2i-1} + D_{2i+1} + 0.5 \cdot D_2^{i+1}}{2} \\
D_2^m = \frac{D_{2i-1} + D_{2i+1}}{2},
\]

where \( i \) from 1 to \( m \) is the thread turn number, \( n \) from 1 to 5 is the number of filtration cycle.

For further convenience, the value of the average diameter of the thread is taken as \( D_2 = \frac{1}{m} \sum_{i=1}^{m} D_2^i \).

The value of the interval of fluctuation of the average diameter over the measurement length \( L_u \) is calculated using the equation:

\[
OD2 = \max(D2) - \min(D2)
\]

For the roller length \( L_R \) value specified in the design documentation, the number of full turns \( n \) that fit this length is calculated:

\[
n = \frac{L_R}{S_p}
\]

then for each turn, starting with \( n \), the actual value of the interval of change in the average diameter on the length of the roller is calculated according to the formula:

\[
OD2_{ri} = \max_{(i-n-1)} \cdots \min_{(i-n-1)} (D2)
\]

where \( i \) is the turn number.
5.3. Calculating the actual tolerance a given profile shape

Based on the functional purpose of the part, the tolerance of the shape of a given profile has different values on different segments of the thread contour. It is normalized in the form of three circuits: nominal, external maximum permissible circuit and internal permissible circuit. The assessment of the actual value of the profile tolerance is carried out by calculating the actual value of the distance from the corresponding point of the nominal profile to the point of the detected profile and comparing this point with two valid contours. For each turn, the coordinate system is transferred to the center point of the inscribed circle, the coordinates of the profile points in the new system $x_{csi}$, $y_{csi}$.

![Figure 7. Assessing the tolerance of a given profile shape](image)

![Figure 8. Result of the tolerance assessment of a given profile](image)
For each point of the measured contour, we find the two closest points of each contour of the nominal profile. At the points of the nominal contour, we flatten the coordinate system (Figure 7). The $y$ coordinate of the obtained point shows the actual value of the tolerance of the shape of the given profile $PR_i$, and the $y$ coordinate of the upper and lower contours show the permissible deviation for this point. The obtained value and the decision on the suitability or non-suitability of the point are written in separate columns of the data point table. For each segment of the contour, we determine the percentage of points within the tolerance and the maximum and minimum deviations. The control results are displayed in the form of a profile scan (Figure 8) where the coordinate of the $x$ point relative to the center of the inscribed circle (in mm) is plotted along the abscissa axis, and the actual tolerance value of the given $PR$ profile in micrometers is plotted along the ordinate axis. The flatten coordinate system is built separately for each thread start and thread contour.

6. Conclusion

The developed technique for standardizing the accuracy parameters of the roller-screw gear made it possible to provide an integrated approach to the design of structures based on their operational characteristics of bearing capacity, the number of operation cycles under various conditions in the CAD structure.

The productivity and reliability of the processes of metrological evaluation of the parameters of the roller-screw gear are increased, so the operational time of control operations is reduced by 45 percent. Currently, roller-screw gears are promising for converting rotational motion into translational motion, and surpass similar solutions in most operational parameters.

Their operational characteristics: stiffness, bearing capacity, kinematic accuracy, positioning accuracy, are most affected by the error in the manufacture of the internal thread profile in terms of pitch, the errors in the interval of change in the actual dimensions of the average diameter and tolerance values for a given profile. Therefore, high-quality standardization of thread profile parameters and full objective metrological control of the thread became relevant and highly responsible.

The article is devoted to the method of standardizing the parameters of threaded profiles implemented in the production environment for the purpose of their application in the conditions of CAD of roller-screw gears and metrological control of the parameters when measuring profiles in the axial plane on a Mitutoyo SV-C4500 contour meter.

To process the measurement results obtained in the process of metrological control, mathematical and software have been developed that are used to analyze and evaluate the quality of mass-produced products.

The developed software is universal for threads with a symmetrical profile of the side surface formed by both straight and arc segments, and therefore can be used in metrological evaluations of screws and rollers of roller-screw gears.

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