Improving the efficiency of setting up a five-axis CNC machine in processing of helical gears using a three-dimensional probe

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Abstract. The most universal method of gear cutting is the method of processing the gear rims of wheels with a universal tool - disk cutters. The main dimension parameter of the gear ring, which is key for ensuring the efficiency of the gear train, is the length of the overall normal. Accurate determination of this parameter is possible only if withdrawal after trial machining and measuring it on a dedicated co-ordinate measuring machine, lost time for the process measurement details, there is a risk of adjustment in marriage. The article considers a method for measuring the length of the General normal of a skewed cylindrical wheel, which allows obtaining its exact value without removing the part after gear processing and measuring this parameter if only one cavity of the gear wheel is processed. Measurements are made using a three-dimensional linear measurement probe. Formulas for calculating the length of the General normal are given, which allow calculating the value of the length of the General normal based on the data of a three-dimensional probe. Comparison of the measurement data of gears with a three-dimensional probe and a specialized CNC gear measuring machine allows us to conclude that the measurement accuracy is sufficient in comparison with the accepted tolerance for the length of the General normal. The introduction of the method of measuring the length of the common normal with a three-dimensional indicator allowed to completely eliminate the probability of commissioning defects and reduced the complexity of carrying out machine changeovers in the mode of single and small-batch processing of gears.

1. Introduction
The most versatile way to manufacture bevel gears is to manufacture them on a five-axis CNC machine. Processing is performed by a universal tool-a cylindrical cutter with replaceable polyhedral plates. In contrast to specialized processing-gear milling with worm cutters with a universal tool, there is no need to manufacture an expensive specialized tool – worm cutters. This method is especially preferable for single and small-scale production of straight-toothed, skew-toothed gears (figure 1 b), as well as shafts-gears with several crowns (figure 1 a). Foreign manufacturers produce tools for this type of processing, consisting of a housing, a vibration-resistant mandrel and hard-alloy non-sharpenable plates, and develop software products for processing gears exclusively for their tools [1]. There are attempts to develop more universal solutions for gear wheel processing [2, 3, 4]. However, the authors do not introduce feedback in the form of measurements of any gear parameters to improve the accuracy of processing or adjustment.

When switching from one gear design to another, the machine is set up on a numerically controlled machine. Commissioning consists in installing clamping mandrels made for the design features of the
processed gear wheel, developing and debugging the program for processing the gear rims of the wheel, performing trial processing.

![Figure 1. Working areas of a five-axis machining machine a) multi-shaft gear shaft, b) gear shaft.](image)

In the case of single and small-scale production of gears, and especially multi-shaft shafts, it is undesirable to have an adjustment defect, since the cost of manufactured products increases sharply, so it is necessary to completely exclude adjustment defects in each technological operation of their manufacture.

The program debugging process is a responsible process of hardware readjustment. Because set during changeovers clamping snap-in has its individual variations, varying degree of tool wear and process parameters of processing, the inaccuracy of machining of gear rims is different. Error compensation is performed by making adjustments to the machine module control program to ensure the key parameter. The key parameter after gear milling is the length of the overall normal (figure 2 a). This parameter is used for product acceptance at the subsequent finishing operation—gear grinding with worm wheels. The length of the General normal should provide a guaranteed amount of allowance on the side surfaces of the teeth of the toothed crown.

The process of debugging the machine system and processing program is performed in the form of trial processing and measuring the length of the overall normal. After processing, the part is removed and measurements are performed by the CNC measuring center in automated mode [5] in the case of detected inconsistencies, repeated processing of the part will not be possible.

The measuring system of the CNC machine is equipped with a measuring probe f. Renishaw (figure 3 a). This probe is normally used to measure the geometric parameters of the processed elements of parts—the diameter and linear dimensions of geometrically simple elements of parts. It is not possible to use it to measure the length of the overall normal, because to perform measurements, you must calculate the coordinates of the probe tip supply to the side surfaces of the gear wheel, as well as based on the design parameters of the gear wheel and determine the length of the overall normal. The machine's CNC system cannot perform the necessary calculations.
On-the-job Adjusters can only measure the length of the General normal with universal measuring tools without removing the part. The size of the total normal length obtained as a result of measurements is used to make a correction to the workpiece processing program for the next gear wheel in order to either increase or decrease the thickness of the teeth in order to achieve the specified allowance for grinding the side surfaces in a CNC gear grinding operation. Practice has shown that the measurement of a universal tool does not allow you to achieve the required measurement accuracy. As a result of an erroneous value of the General normal, there are cases of insufficient allowance for grinding on the side surfaces of subsequent wheels, as a result of which it is impossible to provide the specified tooth thickness along the dividing circle after grinding.

2. Theoretical part
The reason for erroneous measurements is the processing of the crowns of the gear wheel with insufficient tool runs, which leads to a concave shape of the tooth profile. The concave shape of the tooth profile leads to contact of the measuring elements of the universal tool at other points. The scheme of the indicator error formation is shown in figure 2 b. It is possible to eliminate the error by increasing the tool run, but in most cases this is not possible due to the dimensional limitations of the parts being processed and the insufficient range of movement of the machine calipers.

In such a situation, it is necessary to consider possible alternative options for measuring the length of the General normal, the use of which is devoid of the above restrictions. For example, the authors [6] measure the overall normality of the teeth of a gear wheel based on computer vision. This method cannot be implemented in the working area of the machine because video cameras cannot provide the necessary measurement accuracy in the working area of the machine with vibrations and coolant supply. The authors have developed a software module that allows forming the text of the control program for processing the gear wheel based on the original design data, directly without building a three-dimensional model of the gear wheel [7]. The calculation of coordinates of points of working moves is carried out taking into account the structure of technological errors of the machine system [8, 9].

Factory technologists can generate a processing program only if there is a three-dimensional model of the processed crown with typical variants of working moves available in various CAM systems, for example [10, 11]. With this method of processing, it is not possible to ensure optimal movement paths of the cutting tool. Development and testing of the program for the machine can take from several hours to several days. In some cases, it is not possible to get an acceptable processing option due to the user restrictions of the universal CAM system. But even with an acceptable processing program, it is impossible to make measurements of the length of the General normal, since the coordinates of the input of the measuring probe are also unknown.

The authors developed a method for measuring the normality using machine modules and a CNC system of the machine using a three-dimensional MarTest 802 EW indicator for performing measurements (figure 3 b). This indicator is used to find the zero points of the machine, and is performed in a protected version. The indicator is inserted into the tool magazine of the machine to perform operational measurements.

![Figure 4. Schemes a) the contact of the measuring tip with the surfaces of the teeth when measuring the length of the General normal, b) measuring the indicator.](image)

To measure the length of the overall normal, place the spherical tip of the indicator relative to the sides of the teeth (figure 4A). The center of the tip will occupy consecutive positions at points 1 and 2, characterized by its touching the sides of the teeth that limit the length of the General normal W with an allowance for subsequent processing $\Delta S$. When measuring in the end section, the end length of the total normal (with allowance) is calculated using the formula:
where $W_t$ is the length of the General normal in the normal section (without allowance),
$\Delta S$-normal allowance to the side surface of the tooth;
$\beta_b$ - the angle of the teeth on the base circle.

The theoretical coordinates of points 1 and 2 are calculated using the following dependencies:

$$X_t = \frac{W_t}{\cos \beta_b}$$
$$Y_t = \frac{D_b}{2}$$

where $d_0$ is the diameter of the spherical tip;
$D_b$-diameter of the main circle of the gear wheel.

Taking into account the fact that the deviation of the overall normal length size on the processed part
can be either positive or negative, the $X$ coordinates of the supply points should be adjusted by the
guaranteed crossing value $\Delta X=0,1...0,3$ mm. With this in mind the coordinates of the tip points are
defined as follows:

$$X_1 = X_t + \frac{d_0}{\cos \beta_b} + \Delta X$$
$$Y_1 = \frac{D_b - d_0}{2}$$
$$X_2 = X_t + \frac{d_0}{\cos \beta_b} - \Delta X$$
$$Y_2 = \frac{D_b - d_0}{2}$$

The tip is supplied to the measurement points by the CNC program with a conditional stop in them.
Fixing the indicator readings in the form of deviations $\Delta R_1$ and $\Delta R_2$ with subsequent input into the
program module of the tooth processing is carried out by the CNC machine adjuster.
The actual coordinates of the center of the measuring tip $X_{R1}$ and $X_{R2}$ (figure 3 b) will depend on the
actual value of the total normal length and can be determined using the formulas:

$$X_{R1} = X_1 + \Delta R_1$$
$$X_{R2} = X_2 + \Delta R_2$$

where $\Delta R_1$, $\Delta R_2$ is the indicator reading at points 1 and 2, respectively.

The actual value of the total normal length in the end section $W_t$ is determined by the formula:

$$W_t = X_{R1} + X_{R2} - \frac{d_0}{\cos \beta_b}$$

The actual value of the total normal length in the normal section $W$ is determined by the formula:

$$W = (X_{R1} + X_{R2}) \cdot \cos \beta_b - d_0$$

The measured values of the total normal length are used for automated correction of the control
program without the use of NC correctors.
The correction value is calculated as the difference between the calculated length of the General
normal (with allowance) and its actual value:

$$\Delta W = \frac{W_t}{2} - W$$

The found correction value is entered into the software product, forming the control program of the
five-axis CNC machine.

3. Practical implementation and conclusions.
The measurement accuracy will depend on the positioning errors of the milling machine system [12].
The results of measuring the length of the general normal of gears on the machine using a three-
coordinate indicator were compared with the results of measurements of the same gears on a gear
measuring coordinate measuring machine f. Gleason. Deviations of the length of the general normal
did not exceed 0.03 mm, which is an acceptable value to provide an allowance on the sides of the teeth
of the ring gear for grinding 0.15 mm.
Thanks to measurements, without removing the workpiece gear wheel, the efficiency of the machine adjustment process in the process of small-scale processing of gears, reduces the probability of commissioning defects. The method of measuring deviations of processed elements of parts using a CNC system increases the efficiency of diagnosing the technical condition of machine components.

4. References

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