AXIS DETERMINATION FOR CALCULATION OF VIRTUAL PITCH DIAMETER OF A THREAD GIVEN BY POINT CLOUD FROM CMM

I.A. Shchurov, *South Ural State University, Chelyabinsk, Russian Federation, igor_shurov@mail.ru*

Measurement of thread surfaces accuracy is a subject of this investigation. The standard complex indicator of thread accuracy – the virtual pitch thread diameter (VPTD) is considered. The author previously developed and published the method of calculation of VPTD. This method is based on data, which are obtained from coordinate measuring machines (CMM). However, using this method the preliminary determination of the thread axis position is assumed. Actually this case does not always occur in practice. This disadvantage limited the possibility of CMM application for the assessment of the thread accuracy significantly.

Taking it into account, the additional method for the thread axis determination for the cases where the axis is located arbitrarily is offered in this article. This method includes two stages. One of them is based on the determination of average values of point cloud coordinates received from CMM. The second one is based on minimization (maximization) of objective function. The objective function, in turn, includes such parameters as parameters of thread location in CMM coordinate system. VPTD is used as the minimized (maximized) value. The concerned method is confirmed by computer calculations, which show sufficient reliability and «robust» algorithm of the accepted approach.

Calculations were done with point cloud calculated theoretically by using other computer program, and also with points that were received from CMM in real measurement. This investigation determined sufficient minimum number of points to obtain the reliable result at the first most effective stage of the method. Thus, the research showed that for VPTD assessment the earlier offered method and the additional new method gives a possibility to use CMM instead of using gauges.

Keywords: virtual pitch thread diameter, coordinate measuring machine, point cloud.

Introduction. Thread surfaces are widely used for assembling of various components. Very often the accuracy of a thread has to be high. On drawings this condition is set up by the tolerance grade. According to the standards GOST 16093–2004 or ISO 965–1998 thread accuracy is determined by the tolerances of pitch diameters. According to the standard GOST 11708–82 tolerances of such diameters are determined by virtual pitch thread diameters (VPTD) and simple pitch one simultaneously. Obviously, the first one is more complex and will be the limiting factor. Thus, in practice, determination of thread accuracy is usually achieved by measuring its VPTD.

Measurement of such parameter is often carried out by limit gauges (see GOST 24939–81). For measurement of the widespread standard threads the specialized companies make kits of such gauges using GOST 24997–2004, GOST 24475–80, GOST 8867–89, etc. [1]. However, to measure of not so widespread ones, for example, special Buttress threads (see GOST 26250–84 or published book [2]) gauges need to be ordered specially. Obviously, last case leads to increased production costs. Considering modern small-batch production such orders increase its total costs significantly.

There is one way to reduce the cost of thread measuring. This way is using coordinate measuring machines (CMM), which lately are widely distributed. However, such machines are not supplied by the software for VPTD measurement [3, 4]. As a result, many researchers develop specialized program modules for thread measurement by CMM [5]. But, in their publications the calculation of VPTD still is absent [6–8]. Thus, development of a cheap and reasonably accurate method of VPDT measurement on CMM is an important problem of mechanical engineering.

Previously the author of this paper has developed a method of calculation of virtual pitch thread diameter using the point cloud from CMM [9]. One of disadvantages of this method is the need of thread axis definition a priori. However, existing methods of axis definition by using internal or external diameters, by using workpiece coordinate system, in which the thread was cut on the CNC machine tool, are not so accurate.

As a result, the author set himself a task to improve the mentioned above method by development of an additional method of the perfect thread axis determination, which is used for the definition of VPTD. This method is reviewed below and includes some stages. This paper is organized as follows: the first section describes the design diagram and accepted assumptions. The second one describes solutions and order of method realization. The accuracy and efficiency of the proposed method is demonstrated with some computer modelling examples in the third section. In conclusion, sections 4 and 5 summarize the results and recommendations.

1. Problem statement and assumptions. First of all, only cylindrical screw threads are considered in this method. As basic data, a point cloud, which is obtained by thread surface scanning with CMM, is used. Such cloud has to cover the thread surface on all its length or length of engagement. Actually, cases with various thread lengths, including short threads with two or three turns (pitches) are known. In this case, the method provides for existence, at least, of two pitches on the thread. Obviously, coordinates of points will be originally determined in CMM coordinate system. Such system is defined as CS_1 (X_1, Y_1, Z_1). It is also obvious that axis of actual thread is an ideal concept. If each radial section with ideal form had a central point the set of such points would create a rectilinear axis. But also in this case, the mentioned sections are not perfectly located relative to each other. So this axis is curved, i.e. it is a curved line. Thereby, the definition of actual thread axis loses its meaning. So, the ideal thread axis, which is used to define an actual thread, may be considered as a term for this method.

Let's assign such axis as Z-axis of imaginary perfect thread (IPT), which is used in GOST 11708–82 and ISO 5408–1983. The other two axes can be placed anyhow. Such system is defined as CS_2 (X_2, Y_2, Z_2). Therefore, VPTD calculation method is connected with the determination of CS_2 and its axis Z_2 in CS_1 (fig. 1), and with the determination of point cloud in such CS_2.

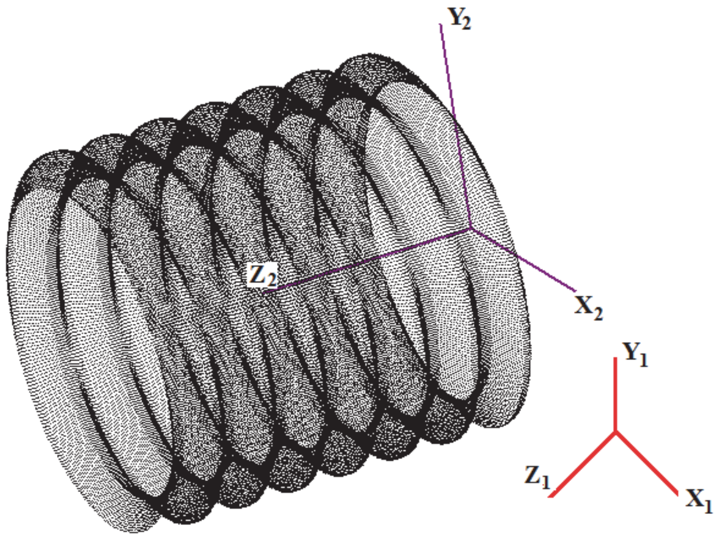

Fig. 1. CMM and IPT coordinate systems

2. Calculation method. As it was mentioned above, IPT axis determination consists of two stages. Such division is mostly connected with computer processing power. The first stage, a rough stage is based on the approach, which defines the approximate position of an IPT axis reliably and quickly. The second stage, a refining stage, is based on the procedure that demands a lot of calculations. But this quantity is significantly reduced thanks to the first stage.

The first stage includes approximate definition of IPT axis position in CS_1 and this stage is based on the determination of average points for point sets received from CMM. Usually all the thread surfaces are made by one tool: a tap (or a finish one from a tap set), a thread-cutting die, a thread-cutting head, a thread-milling cutter or other thread cutting tools. Because of this, cylinders of its major and minor diameters and helical surfaces are essentially related to one another. So, using all points of thread surface to calculate of its axis is reasonable for the first stage.

Initially, two sets of points are taken out of all mentioned above point cloud. The first set S_1 is taken out from the points which are found from the thread left radial section to the section located at one pitch distance from it. The second set S_2 is taken out similarly from the right radial section. For these two sets their average points are calculated, respectively: $T_1(x_{11}, y_{11}, z_{11})$ and $T_2(x_{12}, y_{12}, z_{12})$, where the first index at coordinates indicates number of the coordinate system, and the second one is the point number. These two points define the initial position of a required axis in CMM system. Coordinates of these points may be calculated as:

$$x_{11} = \frac{\sum_{i=1}^{L} x_1^{(i)}}{L},\ y_{11} = \frac{\sum_{i=1}^{L} y_1^{(i)}}{L},\ z_{11} = \frac{\sum_{i=1}^{L} z_1^{(i)}}{L};$$
$$x_{12} = \frac{\sum_{i=N}^{R} x_1^{(i)}}{R},\ y_{12} = \frac{\sum_{i=N}^{R} y_1^{(i)}}{R},\ z_{12} = \frac{\sum_{i=N}^{R} z_1^{(i)}}{R}, \tag{1}$$

where L and $(R - N)$ are numbers of points in sets S_1 and S_2, respectively; $x_1^{(i)}$, $y_1^{(i)}$, $z_1^{(i)}$ are point coordinates in these sets.

Coordinates of other points can be determined in the coordinate system with axis Z aligned with the axis which passes through these two points. For this purpose the rotational angles θ and ψ for rotational matrices have to be determined:

$$\mathrm{tg}(\theta) = (x_{12} - x_{11}) / (z_{12} - z_{11}),\ \mathrm{tg}(\psi) = (y_{12} - y_{11}) / \sqrt{(x_{12} - x_{11})^2 + (z_{12} - z_{11})^2}\ . \tag{2}$$

Then new point coordinates in system CS_3 are

$$\begin{pmatrix} x_{3j} \\ y_{3j} \\ z_{3j} \end{pmatrix} = R_Y(\psi) R_X(\theta) \left(\begin{pmatrix} x_{11} \\ y_{11} \\ z_{11} \end{pmatrix} + \begin{pmatrix} x_{1j} \\ y_{1j} \\ z_{1j} \end{pmatrix} \right), \tag{3}$$

where $R_Y(\psi)$ and $R_X(\theta)$ are basic rotation matrices around axes Y and X to the angles θ and ψ, respectively; x_{1j}, y_{1j}, z_{1j} are coordinates of point cloud in CMM system CS_1.

In such a manner, on this stage approximate location of ITP axis and coordinates of point cloud in system CS_3 may be found. After that, using previously developed method [9], VPTD has to be calculated. Further, this parameter is taken as the basic diameter (BD). To refine position of mentioned axis the second stage is proposed.

The second stage is caused by the uncertainty of the IPT position in every practical case. This stage is based on such surface fitting by minimization of an objective function. Obviously, this function is VPTD. Parameters of this function represent the position of IPT in system CS_3. These parameters are the same for basic matrices of linear and rotational transformation in equation (3). So, the second stage includes rotation and translation of given axis in system CS_3 which minimizes VPTD. Considering large computation time to calculate VPTD using present day computers, this stage can be optimized by using well-known multivariable extremum seeking algorithms. However this optimization algorithm isn't a subject of this article.

The stage under consideration is separated into two steps, which are related to the mentioned above coordinate system transformations. Such separation is necessary because in some cases the calculation of the required axis may be finished at any stage or its step. The finish condition is reliant on the accuracy of calculations. All of this reduces the calculation time.

So, *the first step* is related with rotation of axis Z_3 to a small angle τ. This rotation has to be performed into the transformation plane that passes thought the same axis Z_3. For example, this rotation may be executed around axis X. After that, the calculation of the point cloud coordinates by using similar equation (3) should be made. Later this coordinates are used to calculate VtPTD [9]. If this diameter is equal to BD, the angle τ should be increased until the minimum of VPTD will be obtained. However, soon after that, VPTD will start to increase again and this position defines the minimum.

After that, the rotation of the mentioned above transformation plane to a small angle φ around axis Z_3 should be performed. The procedure with angle τ has to be repeated as it was described before. Evidently, there is a need to compare the obtained VPTD with each other and to determine its minimum. Such rotation of the angle φ has to be repeated up to 360 degrees. When the found axis position gives the minimum VPTD the determined angles τ and φ will be the result of such procedures.

After that *the second step* has to be executed. It is associated with the translation of the axis Z_3 along the coordinate axes. The most important transverse translation direction was revealed with our previous calculations. Taking into account two mentioned above points T_1 and T_2 these translations have to be performed. Average value of the coordinates: x_{11}, y_{11} and x_{12}, y_{12} is the parameter of the second matrix on the right side of the equation (3).

Further, the mentioned procedures of these two stages may be repeated one after another. When VPTD increment of the last iterations is less than a prescribed value (part of micrometer) the procedures should be stopped. The obtained value of VPTD is the final solution.

3. Computer modelling. Based on this method, computer software has been developed to verify it.

The first program was connected with the first stage of the method. The assessment of axis position accuracy depending on the quantity of points from CMM was the purpose of these calculations. As an example, thread M12×1,75 was examined. The point cloud was obtained from the part of this thread with radial sections from section z_1 = 1 to section z_2 = 13. The step of the location of these points along axis Z was equal to 0,1 mm.

For accuracy assessment, point cloud was received from the perfect thread surface, which was calculated by the computer program that was developed in previous years. In these calculations the thread axis was perfectly located along axis Z_1. On the whole there were five examples with various numbers of points: from 13 000 to 87 000. Calculation results are shown in the table, the points are shown in Fig. 2.

As shown in the table, the rotation angle can reach 0,1 degree (column 9) and axis translation in the radial direction can reach 35 microns (column 10). So, on the second step to calculate the initial values: τ and radial offset these parameters should be used.

Coordinates of points T_1 and T_2

№	Number of points	Coordinates T_1, μm			Coordinates T_2, μm			Axis rotation angle, deg	Radial translation, μm
		x_{11}	y_{11}	z_{11}	x_{12}	y_{12}	z_{12}		
1	2	3	4	5	6	7	8	9	10
1	87 000	0,00	0, 00	1850	0,00	0, 00	12150	0, 00	0, 00
2	65 000	3,09	–6,93	1866	–3,09	–6,93	12133	0,034	–7,59
3	43 000	2,55	–6,76	1850	–2,55	–6,79	12150	0,028	–7,22
4	22 000	1,42	–7,32	1800	–1,42	–7,32	12200	0,016	–7,45
5	13 000	10,22	–32,62	1833	–10,22	–32,62	12167	0,113	–34,18

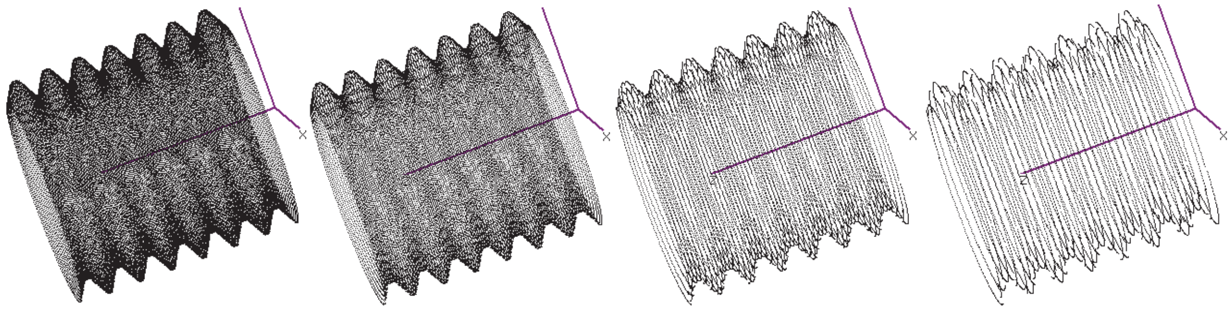

Fig. 2. Points of the thread surface: 65 000, 43 000, 22 000, 13 000

Other calculations show that using of more than 100 000 points is not appropriate: deviations of points T_1 и T_2 are less than 0,001 μm. Also these calculations show that the first stage may be sufficient if the number of points is around the mentioned limit value. Now, this quantity of points is achievable for laser scanner like LC15Dx, which has scanning speed equal to 70 000 points per second and measurement error equal to about 5 microns [10].

The second program was connected with the second stage of the method. As an example, thread M32×2,5 with point cloud from CMM "KIM-1000, Lapic" was examined. In this case using the contact method the points of four cross-sections of the thread in two perpendicular axial planes were got (Fig. 3).

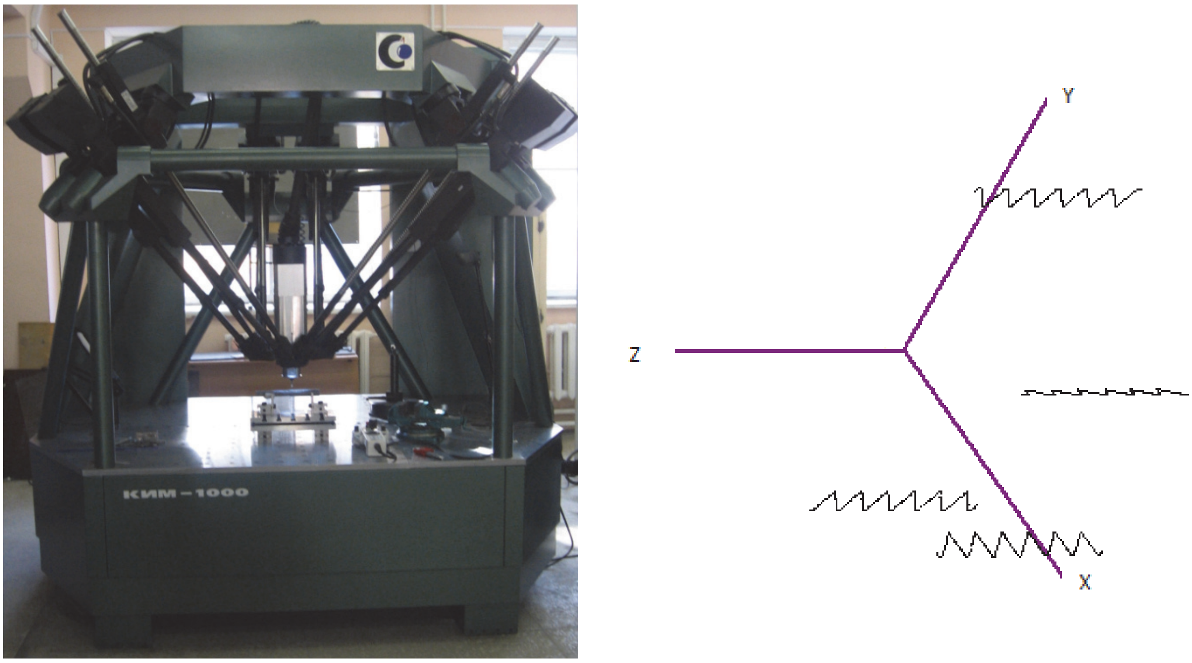

Fig. 3. CMM "KIM-1000, Lapic" and points of thread M32×2,5

The VPTD obtained on the first stage was equal to 31,075 mm. After axis rotations to angles τ equal to 0,00001; 0,0001; 0,001 degrees VPTD variations were not observed. Only after the rotation to the angle τ equal to 0,01 degrees the VPTD was decreased to 30,950 mm. The subsequent decrease of τ caused the increase of VPTD again and, therefore, at this stage the received value is minimal. The use of the formulas of the second step didn't cause the received size change. Thus, in this case VPDT is finally equal to 30,950 mm, it corresponds to the calculated value for this thread with perfect axis position.

4. Conclusions. Proposed method of the axis determination to calculate the virtual pitch diameter of a thread given by point cloud from CMM is reliable and produces the results, which correspond with the expected values. This investigation shows that the most perspective way is VPTD measurement by using the maximal quantity of points (about 100 000). The first stage of the method based on the search of the average values of coordinates, is the most reliable and "robust". However for the short threads, which have only two pitches, and for the small points number (less than 10 000), the second stage based on minimization of objective function is required.

5. Discussion and application. The use of CMM and the methods described above gives the possibilities to eliminate thread gauges using. It reduces the production cost, particularly for modern small-batch manufacturing. Beyond the scope of the considered method there is the problem of the influence of measurement error on the results. Also the problem of the optimization of the second stage of the method is not discussed. However, the received solutions, computer programs and test calculations show that this method may be used in practice for the thread measurement using CMM.

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Received 13 August 2014

Bulletin of the South Ural State University Series "Mechanical Engineering Industry" 2014, vol. 14, no. 3, pp. 76–82

УДК 621.9.08

ОПРЕДЕЛЕНИЕ ОСИ ДЛЯ РАСЧЕТА ПРИВЕДЕННОГО СРЕДНЕГО ДИАМЕТРА РЕЗЬБОВОЙ ПОВЕРХНОСТИ, ЗАДАННОЙ ОБЛАКОМ ТОЧЕК ОТ КИМ

И.А. Щуров

Исследование посвящено измерению точности резьбовых поверхностей. Стандартный комплексный показатель такой точности – приведенный средний диаметр резьбы (ПСДР) – является предметом статьи. В ранних исследованиях автором была разработана и далее опубликована методика расчета ПСДР на основе данных, получаемых на координатно-измерительных машинах (КИМ). Однако такая методика предполагала заранее известным положение оси резьбы, что, очевидно, не всегда встречается в производственной практике. Такой недостаток существенно ограничивал возможность применения КИМ для оценки точности резьб.

Исходя из этого, в предлагаемой статье дана дополнительная методика для расчета оси произвольно расположенной в пространстве резьбы. Такая методика включает два этапа. Первый основан на определении средних значений координат точек облака, полученного от КИМ. Второй – на последующей минимизации (максимизации) целевой функции. Такая целевая функция, в свою очередь, в качестве параметров включает параметры положения оси резьбы в системе координат КИМ. В качестве минимизируемой (максимизируемой) величины используется сама величина ПСДР. Полученная методика подтверждена компьютер-

ными вычислениями, которые показали достаточную надежность принятого подхода и «робастность» алгоритма.

Вычисления производились как с использованием точек, рассчитанных теоретически с применением отдельной компьютерной программы, так и точек, полученных на практике с использованием КИМ. Данными исследованиями установлены минимально достаточные величины числа точек для получения надежного решения уже на первом, наиболее эффективном этапе реализации методики. Таким образом, исследование показало, что предложенная ранее методика в дополнении с новой позволяют использовать КИМ вместо калибров для оценки ПСДР.

Ключевые слова: приведенный средний диаметр резьбы, координатно-измерительная машина, облако точек.

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Щуров Игорь Алексеевич. Доктор технических наук, профессор кафедры «Технология машиностроения», Южно-Уральский государственный университет (Челябинск), igor_shurov@mail.ru.

Поступила в редакцию 13 августа 2014 г.