中國機械工程學刊第三十九卷第四期第 411~417 頁(民國一百零七年)
Journal of the Chinese Society of Mechanical Engineers, Vol.39, No.4, pp 411~417 (2018)

Experimental Study on Reconstruction Method and Simulation Technology of the Thread Gauge

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Keywords: thread calibration, reconstruction model, coordinate measuring machines (CMM).

ABSTRACT

This paper presents a comprehensive and reasonable method for the calibration of thread gauges. The procedure involves scanning of thread profiles around 360 degrees by the star probes of coordinate measuring machines. The thread model can be reconstructed by collecting the touch points using the homogeneous coordinate equation. To reduce the system error, the probe Cosine error compensation is proposed here. In addition, we establish an ideal model based on ISO 1502. The thread gauge can be judged by comparing the reconstruction model scanned by a CMM with the model given by the standard. The experimental results show a good agreement with the values calibrating in National Institute of Metrology.

INTRODUCTION

In the modern measurement, it is essential to calibrate the thread gauge with high accuracy, which is very important for the system reliability, the assemble accuracy and the load capability. Therefore, the high accuracy calibration of the thread has attracted increasing interests in metrology field.

Paper Received November, 2015. Revised January, 2016. Accepted February, 2016. Author for Correspondence: Yan Zhao

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Traditionally, the thread can be well measured based on the system with a proof gauge, but the measurement accuracy highly depends on the thread form, wear degree and personal error. The method based on the measurement of the parametric features has been developed for a long time. Directly, the measurement of the pitch diameter relies on two balls or three-pin with universal measuring machines, and scanning measuring instrument and coordinate measuring machine can measure several parameters at the same time. The non-contact approach has also been investigated. However, the methods mentioned above show significant inconsistence while measuring the same thread due to the difference of the judgment standard. To solve this problem, it is promising to establish a comprehensive model involving all the interested parameters, which can be reliably judge the thread quality.

In this paper, we propose a comprehensive method for the inspection of the thread. Firstly, we build a practical model by scanning the thread gauge in four vector directions with the CMM. The thread model can be reconstructed accurately with error compensation and using the homogeneous coordinate equation. Secondly, a theoretical model is presented based on ISO 150, which are used to compare with the practical model. The thread quality can be thus judged via the comparison between the practical and the theoretical models. Our experimental results show a good agreement with the reference values given by National Institute of Metrology, China. The combined standard uncertainty for the reconstruction meets the requirement of the measurement precision

MEASUREMENT METHOD

Measurement Principle

The star probe is configured to measure thread gauge by contacting the scanning mode with the CMM. The principle of getting point is as follows: the force curve starts when the probe touches the work-piece. At the point of the maximum force, the head moves along the opposite direction, and between the upper and lower trigger force at least 7 points are collected.

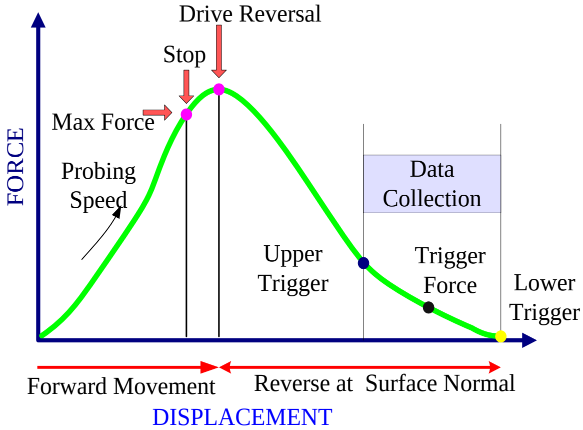

Fig.1: Collection touches point.

$$\theta_l = \theta * l \quad (l=1.2.3\ldots45) \tag{1}$$

Where $\theta = \pi/180$.

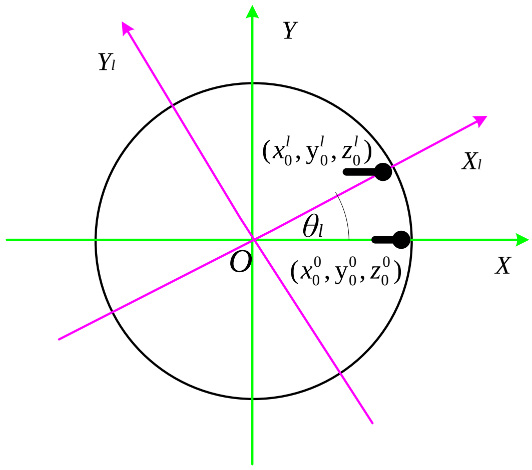

Fig. 2: Coordinate system rotating angle θ_l.

The average value is chosen as the final measurement point, as shown in Figure 1.The CMM needs to calibrate the probe using the standard sphere before measuring the thread gauge. In order to obtain accurate measurement, the star probe is calibrated in scanning mode, using the same speed and measuring force, as the thread measurement. Each profile is probed at the intersection of the screw surface with a plane containing the thread axis. The star head with four probes can scan the two perpendicular pairs of thread profiles. The measurement gives a more complete characterization of the thread if the number of measured profiles is increased. For this reason, we present a method to construct 3D model by scanning thread gauge with 360 degrees.

Construction Thread

To establish 3D model of the thread gauge, the following stages are carried out. Firstly, In order to collect all the scanned points to establish the 3D model, all the points should be put in the same coordinate system. Therefore, we construct an original coordinate system OXYZ shown in Figure 2. The origin is fixed at the central point on the end face of the thread gauge, and the Z axis is coincident with the axis of the thread. Secondly, in the original coordinate system OXYZ, $M_i^{\mathbf{0}}$ is a set of the thread surface point coordinates scanning by the star probes, which can be expressed as $X_i^{\mathbf{0}}$. Please note that, it is important to put the scanning points into the origin of the coordinate system. Thirdly, with the original coordinate system, rotation angle θ_l around the Z axis can be converted into the new coordinate system $OX_lY_lZ_l$, which can be updated to be X_i^l. The rotation angle θ_l changes in a range from -π/4~+π/4 for measuring the thread profile of a circle without rotating the thread gauge or moving the star probe. The angle θ_l is determined by:

Finally, the homogeneous transformation method is used to build the volumetric model generally. An arbitrary point set in the original coordinate system can be calculated as:

$$\begin{bmatrix} X_i^{ol} \\ Y_i^{ol} \\ Z_i^{ol} \\ 1 \end{bmatrix} = \begin{bmatrix} \sin\theta_l & -\cos\theta_l & 0 & 0 \\ \cos\theta_l & \sin\theta_l & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} X_i^l \\ Y_i^l \\ Z_i^l \\ 1 \end{bmatrix} \tag{2}$$

Where the coordinate $X_i^{\mathbf{0}l}$, is transformed into the OXYZ coordinate system by X_i^l. The basic model of the thread is constructed by the collection of all the points. At the same time; the basic characteristic parameters of the screw thread are also calculated by the CMM.

Error Compensation

As shown in Fig. 2, the original coordination system rotates by an angle θ_l, but the head does not rotate that is still along the reference direction. The center point of the ruby ball is obtained when the probe touches the measuring point. The point coordinates of the model should be related to the contacting points between the needle and the thread surface, but not the center point of the measuring ball. The distance between the two points is the stylus radius value along measurement direction (vector) as shown in Fig. 3. This needs to be achieved through the probe head compensation. Then the characteristic points of the thread are obtained.

When the measuring probe contacts to the work-piece, the radius compensation automatically adds to the measured values along the direction of the probe back by the CMM. However, the measurement value is a dynamic value related to the mechanical inertia of the probe. In fact, in this dynamic process, the compensated length should be R*cos(θ_l), as shown in Figure. 3, where R is the radius of the probe, θ_l is the angle of rotation.

At the beginning of the pick point, the measuring software will compensate the measuring ball in the direction of the work-piece along the needle, but the compensation point is not the real point of contact; instead, the point is on the extension line of the direction of the probe. This will cause a "cosine error" shown in Figure. 3.

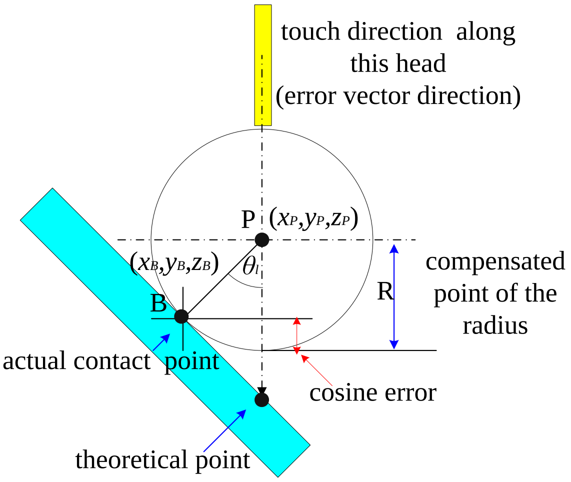

Fig.3: Cosine Error.

The work-piece is measured along the direction opposite to the vector. There is a cosine error caused by the new coordination system with rotating angle θ_l around the Z axis. The coordinates of ruby center point P is (x_P, y_P, z_P) by probing. In the measurement coordinate system rotated by an angle θ_l, the coordinates of the actual contact point B are (x_B, y_B, z_B), and the radius of the ruby probe is R. The error compensation is shown following as

$$\begin{cases} X_B = X_P + R*\cos\theta_l \\ Y_B = Y_P + R*\sin\theta_l \\ Z_B = Z_P \end{cases} \tag{3}$$

Then, the matrix of radius compensation is shown as:

$$\begin{vmatrix} 1+R*\cos\theta_l & 0 & 0 & 0 \\ 0 & 1+R*\sin\theta_l & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{vmatrix} \tag{4}$$

Complete Screw Thread

According to the requirements of the complete screw thread in ISO 1502 and ISO 68-1, the parameters that can determine the shape of the thread are shown in Table 1.

Table 1: Thread Parameter.

Symbol	Representative meaning
d_0	the major diameter of internal thread
d	pitch diameter of internal thread
b_1	The gap width of the complete inner screw thread in the major diameter
P	the pitch of internal thread
α	upper half of the flank angle
β	lower half of the flank angle
γ	lead angle

The symbols of the thread are shown in Figure 4. The Z axis is the axis of the thread， and the positive direction of the X axis is the beginning of thread generatrix. A complete screw thread can be obtained by rotating a circle along the Z axis. The formulas for generatrix of the screw thread are made up of three parts according to Fig. 4.

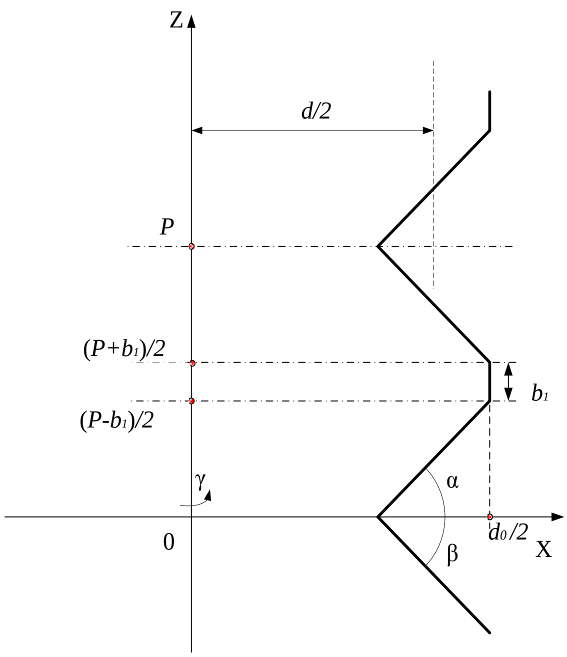

Fig.4: Symbols of the thread in the X-Z plane.

Let us set a parameter U. When $0 \le U \le (P - b_1)/2$, the formula for generatrix of the screw thread is shown as:

$$\begin{cases} x = [U * \tan\alpha + d_0/2 - (P - b_1) * \tan\alpha/2] * \cos\gamma \\ y = [U * \tan\alpha + d_0/2 - (P - b_1) * \tan\alpha/2] * \sin\gamma \\ z = U + 2 * \gamma * P/\pi \end{cases} \quad (5)$$

When $(P - b_1)/2 \le U \le (P + b_1)/2$, the formula for generatrix of the screw thread is shown as:

$$\begin{cases} x = d_0 * \cos\gamma/2 \\ y = d_0 * \sin\gamma/2 \\ z = U + 2 * \gamma * P/\pi \end{cases} \quad (6)$$

When $(P + b_1)/2 \le U \le P$, the formula for generatrix of the screw thread is shown as:

$$\begin{cases} x = [-U * \tan\beta + d_0 + (P - b_1) * \tan\beta/2] * \cos\gamma \\ y = [-U * \tan\beta + d_0 + (P - b_1) * \tan\beta/2] * \sin\gamma \\ z = U + 2 * \gamma * P/\pi \end{cases} \quad (7)$$

The maximum model and minimal model of the standard thread ring gauge can be obtained by the upper and lower limits of theoretical parameters (e.g. b_1, d_0, d, α, β, γ). Standard thread model is obtained by calculation as shown in Figure 5.

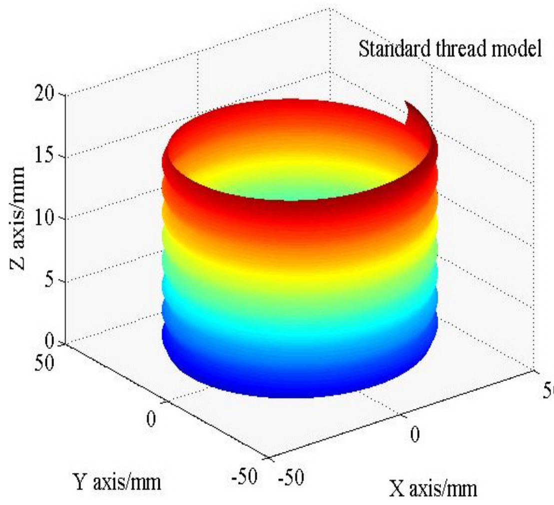

Fig.5: Standard thread model.

EXPERIMENT

Experimental Setup

The CMM "Leitz PMM-Xi 12.10.07" was used for the measurement of the thread gauge with the software system of QUINDOS 7. The CMM used for the measurement has a Maximum Permissible Error (MPE) of 0.6+ L / 600 μm (L in mm). The model of the thread shape reconstruction is shown in Figure 6.

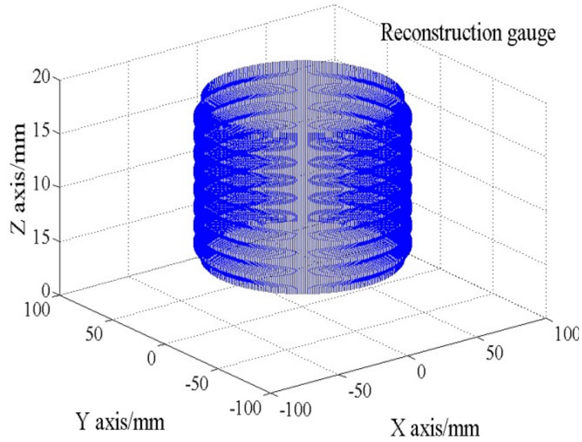

Fig.6: Reconstruction gauge model.

The procedure is applied to measure forty-two different specifications of the threads as described above in section 2.2. According to the principle of error compensation of section 2.3, forty-two pieces of real thread models are obtained. Forty-two thread gauges reconstruction models for the thread gauge are obtained by the CMM. The Standard thread dimensions and tolerances given by ISO 1502 are followed for judging the quality of the measured threads.

In the calculation of the thread parameters, Master Scanner (MSXP 16060) is used to measure the thread parameters. There parameters mainly include minor diameter, pitch diameter, pitch and flank angles. Check plugs consists of Go check plugs and Not Go check plugs. Go check plugs are made to the minimum permitted diameters of the ring within a small negative tolerance; Not Go check plugs are made to the maximum permitted size of a particular element within a small positive tolerance.

Experimental Results

The measurement results are shown in table 2, which are obtained by using three methods, respectively: Reconstruction model, Parameter measurement and Check plugs. Y" means that the thread gauge is good. On the contrary, "N" means bad. Experiment shows that the most results of the three methods are the same.

However, there still have 11 pieces of thread gauges inconsistently.

Table 2: Experiment Results.

Thread specifications	**1.Recon-struction**	**2.Para-meter**	**3.Check plugs**
M30*2-6h GO	Y	Y	Y
M30*2-6h NOGO	Y	Y	Y
M36*3-6h GO	N	Y	N
M36*3-6h NOGO	N	N	N
M36*3-6g GO	Y	Y	N
M36*3-6g NOGO	Y	Y	Y
M48*3-6g GO	N	N	N
M48*3-6g NOGO	Y	Y	Y
M52*2-6h GO	N	Y	Y
M52*2-6h NOGO	Y	Y	Y
M52*3-6h GO	N	N	N
M52*3-6h NOGO	N	N	N
M60*2-6g GO	Y	Y	Y
M60*2-6g NOGO	Y	Y	Y
M72*4-6g GO	Y	Y	Y
M72*4-6g NOGO	N	N	N
M80*2-6h GO	Y	Y	N
M80*2-6h NOGO	Y	Y	Y
M96*3-6g GO	Y	Y	Y
M96*3-6g NOGO	N	N	N
M110*2-6h GO	N	N	N
M110*2-6h NOGO	Y	Y	Y
M120*3-6g GO	Y	Y	Y
M120*3-6g NOGO	N	Y	N
M122*3-6g GO	Y	Y	Y
M122*3-6g NOGO	Y	Y	Y
M125*4-6g GO	Y	Y	Y
M125*4-6g NOGO	Y	Y	Y
M130*6-6g GO	N	Y	N
M130*6-6g NOGO	N	N	N
M135*4-6g GO	Y	Y	Y
M135*4-6g NOGO	N	Y	N
M150*5-6g GO	Y	Y	Y
M150*5-6g NOGO	N	N	Y
M156*5-6h GO	Y	Y	Y
M156*5-6h NOGO	N	Y	N
M158*4-6g GO	Y	Y	Y
M158*4-6g NOGO	N	N	N
M160*2-6h GO	Y	Y	Y
M160*2-6h NOGO	N	Y	N
M160*4-6g GO	Y	Y	Y
M160*4-6g NOGO	N	N	Y

Uncertainty Evaluation

As indicated in table 2, we find the results corresponding to 11 pieces of the gauges show the inconsistency. To verify the performance of our method, we measure these 11 samples in National Institute of Metrology (NIM), and the results are shown in Table 3. A good agreement between our method and NIM can be found. The influencing factors of the measurement results are analyzed. The measurement uncertainties of the three methods are assessed.

Table 3: Results Measured in NIM.

Thread specifications	National Institute of Metrology, China.
M36*3-6h GO	N
M36*3-6g GO	Y
M52*2-6h GO	N

M80*2-6h GO	Y
M120*3-6g NOGO	N
M130*6-6g GO	N
M135*4-6g NOGO	N
M156*5-6h NOGO	N
M150*5-6g NOGO	N
M160*2-6h NOGO	N
M160*4-6g NOGO	N

(1) The reconstruction method will be used to calculate the uncertainty without the need for a calibrated reference thread gauge. The uncertainty contributor related to maximum permissible errors of the CMM, standard deviation of repeat measurement and systematic error, etc. The expanded measurement uncertainty of the measured thread is calculated shown in Table 4.

(2) Most of the important parameters can be measured in only one axial section by IAC the type of MSXP 16060. The uncertainty consisted of the standard uncertainty from the reference ring gauge, the standard deviation of Master Scanner, standard deviation of repeat measurement and systematic error .The expanded measurement uncertainty of the scanning method is calculated in the experiments in Table 4.

(3) Using M80*2-6h-GO as an example is illustrated according to ISO 1502.The thread ring gauge of M80*2-6h-GO, the diameter of which is qualify from 78.6840 mm to 78.7020 mm. The calibration gauges for the test consists of Go check plugs and Not Go check plugs. The diameter of Go check plug is from 78.6705 mm to 78.6795 mm, and the diameter of NOT Go check plug is from 78.6975 mm to 78.7065 mm. Therefore, the diameters between 78.6705 mm to 78.7065 mm of the working thread ring gauge are likely to be judged to be qualified. So there will be deviations in the test. Through a large number of repeatedly trials, the expanded measurement uncertainty of this method is shown in Table 4.

Table 4: The Expanded Measurement Uncertainty

Measurement method	Uncertainty (95%)
Reconstruction	$(2.1+ 2*10^{-3}*L)$ μm
Parameter measurement	$(1.8+5*10^{-3}*L)$ μm
Check plugs	$(2.0+5*10^{-3}*L)$ μm

In Table 4, L is the diameter of the thread gauge given in μm.

The uncertainty of the above three methods can meet the calibration requirements of the thread gauge. Although the value from the reconstruction method is not significant smaller than the others, nevertheless, our method could present results different with the others but consistent with the result traced to national metrology institute. Therefore, it is more comprehensive and accurate to use the reconstruction method.

CONCLISIONS

In this paper, we propose a method of reconstruction model for the thread measurement. Compared with the traditional methods, the reference gauge is not required. In addition, we can scan the total 360 degrees of the thread, not an axial section.

Thread gauge is a complex work-piece with spiral rotation. Through a large number of measurement experiments, the method of remodeling can be used to accurately judge the quality of the thread. The thread model is re-established by scanning 360 degrees using the star probes of CMM and compared with the standard gauge model, which greatly improves the accuracy of the inspection. The reconstruction method can determine the exact interference position of the thread gauge. This method can find the reasons of the failure and provide theoretical support of the influence of different parameters on the design of production and manufacturing. This method can provide a more reasonable theoretical guidance for the design of screw threads.

In future, we will focus on the experimental optimization of the reconstruction model system, which can further improve the accuracy of the measurements.

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基於重塑與模擬技術的螺紋校準試驗研究

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摘 要

本文提出了一種全面合理的螺紋規校對方法。該方法主要是利用座標測量機星型測頭對螺紋進行 360 度掃描，利用齊次座標方程建立螺紋模型。為了減小系統誤差，本文提出了 Cosine 誤差補償。同時，我們根據 ISO1502 建立了標準螺紋模型。通過使用座標測量機掃描建立的螺紋重塑模型與標準螺紋模型比較來校準螺紋規。實驗結果與國家計量院校準結果一致。