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A NOVEL ARTIFACT FOR EVALUATING ACCURACIES OF GEAR PROFILE AND PITCH MEASUREMENTS OF GEAR MEASURING INSTRUMENTS

Sonko Osawa [1], *Osamu Sato* [1], *Yohan Kondo* [1], *Masaharu Komori* [2] *and Toshiyuki Takatsuji* [1]

[1] National Metrology Institute of Japan/ AIST, 1-1-1 Umezono Tsukuba Ibaraki, Japan, sonko.osawa@aist.go.jp
[2] Department of Mechanical Engineering and Science, Kyoto University, Yoshidahonmachi, Sakyo-ku, Kyoto-shi, Kyoto, Japan, komorim@me.kyoto-u.ac.jp

Abstract – Evaluation of measurement performance of a gear measuring instrument (GMI) is not easy task since a master gear with sufficient accuracy has not been available. The manufacturing the master gear with an ideal involute form is very difficult and the accuracy of the master gear is not able to be estimated. Therefore, we have proposed a new artifact named Double Ball Artifact (DBA) which consists of a base plate and two balls for evaluating the gear profile measurement performance by the GMI [1, 2]. It has advantages of inexpensive, accurate, and calibrated with traceability. The DBA, however, is able only to evaluate the profile measurement capability of the GMI. In this paper, we describe a novel artifact evaluating the profile and the pitch measurement performances of the GMI simultaneously.

Keywords: gear, gear measuring instrument, evaluation

1. INTRODUCTION

Although gears are conventional parts, they are still keeping important positions in many industries. Gears have many parameters. Usually, the profile, the lead and the pitch of a gear are evaluated by a gear measuring instrument (GMI). For the evaluating the capabilities of GMIs, the master gears are mostly used. The manufacturing the master gear with an ideal involute form, however, is very difficult and the accuracy of the master gear is not able to be estimated. In addition, there is the problem of high manufacturing cost. And the calibration of the involute shape is another difficult job, and even national metrology institutes (NMIs) are not capable of calibrating an involute form with sufficiently small uncertainty. Therefore, we have developed a novel artifact which is named Double Ball Artifact (DBA) [1] for evaluating the measurement capabilities of the GMIs. The artifact consists of a flat plane and two balls. The plane and the ball are easily manufactured with high accurate form. And the forms are able to be measured by high accurate measuring instruments (e.g. roundness measuring machines, flatness measuring interferometers). Characteristics of the DBA are (1) its form deviation from ideal one is extremely small, (2) inexpensive, and (3) it can be traceably calibrated. Thanks to the characteristic (3) measuring instruments can be traceably calibrated. The DBA, however, is able only to evaluate the profile measurement capability of the GMI. In this paper, we describe a novel artifact which is named Multi Ball Artifact (MBA) evaluating the profile and the pitch measurement performances of the GMI simultaneously.

2. DOUBLE BALL ARTIFACT [1,2]

The double ball artifact (DBA) has a simple structure; namely two balls are placed on a disk. An arc as a part of a cross section of a ball is close to involute curve and the difference between two can be expressed mathematically. As explained later, all parameters needed to calculate the difference can be traceably calibrated. The DBA is easy to make, inexpensive, and traceably calibratable with known uncertainty; consequently it is one of ideal gauges. The ISO/TC 60 adopted the DBA in ISO/TR 10064-5 [2] and the details of the analyzing method are described in its appendix. It is a good practice to select a master gauge of the same dimension as gears actually used. The DBA can be applicable to various size gears by changing the size and interval of the balls.

The involute curve and the arc have slightly different forms; nevertheless the difference can be represented mathematically. Compensation of the difference enables the arc to serve as a virtual involute curve. The theoretical and measurement values of the difference correspond to the measurement performance of the instrument. The shape of the difference changes with the diameter and interval of the balls. By appropriately selecting these parameters, a curve which looks like a camel back is obtained as shown in Fig. 1. Equation 1 is a guide line to design the interval C of the DBA, from which two peaks of the camel back show almost the same height each other.

$$C \approx 0.994\, r_b + 0.038(r_c + r_p) \qquad (1)$$

where r_b is the radius of the base circle, r_c is the radius of the form checking ball, and r_p is the radius of the probe used to measure the DBA.

Dimensions of the DBA should be designed with taking that of gears actually used. In this experiment, considering easiness of obtaining balls we selected a 1 inch (=25.4 mm) ball. For the measurement probe radius of 1 mm, and the base circle diameter of 43.75 mm, the interval of the balls was designed to be 44.008 mm. Fig. 2 shows the DBA. The balls and the base plate are made of a steel and a low

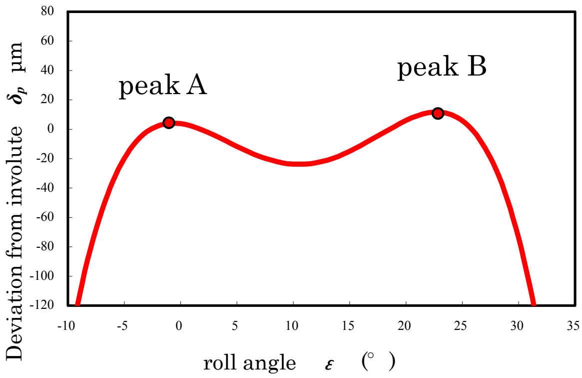


Fig. 1. A typical camel back curve, i.e. the difference between a theoretical and measurement data when the DBA is measured

Fig. 2. Photo of the double ball artifact (DBA)

thermal expansion glass respectively. This figure shows the low expansion type.

Parameters to be calibrated are only the radius of the form checking ball and the interval of the two balls. Although mass product bearing balls are inexpensive, they have extremely good sphericity (less than 50 nm) and uniform radius. Sphericity (roundness) and radius can be traceably calibrated by NMIs, consequently the DBA can be a traceable artifact. The DBA has two balls, namely it can be regarded as a double ball bar or a ball plate which are commonly used to calibrate CMM. These gauges are generally calibrated by many NMIs, hence the DBA can be calibrated without additional modification to a routine calibration procedure. Since all necessary parameters of the DBA are calibrated with traceability, the DBA itself can be treated as a traceably calibrated involute master.

NMIJ has developed a special instrument for calibrating the length between two spheres. Fig. 3 shows the instrument. The length between two spheres is precisely calibrated by an interferometer.

Fig. 4 is an example of a measurement result. The TCB and MCB mean the Theoretical Camel Back curve and Measured Camel Back curve respectively (refer the scale of the left side). Due to the difference of the definition of the rolling angle, these two curves do not overlap each other, and the MCB can be shifted to overlap with the TCB as closely as possible. After shifting the MCB, the deviation from the TCB is calculated and drawn in the Fig. 4, which is indicated by DCE (Deviation Curve for Evaluation) (refer the scale of the right side). The DCE curve corresponds to the measurement, i.e. approximately 2.5 µm peak-to-peaks.

When the instrument has any error factors, the MCB is not an ideal camel back curve. Because many errors are related each other and give complicated effect to the measurement result, error factors cannot be determined from the measurement result uniquely. Nevertheless if we assume only a few error factors which are likely to occur exist, the error factors can be identified with considerably small uncertainty. If we assume the base circle radius has 0.001 mm error, the gain of the probe has -6.6 % error, and the scale of the probe stage has -0.12 % error, the DCE in the Fig. 4 becomes the CDCE (Corrected Deviation Curve for Evaluation). The error of the instrument looks extremely small.

The assumptions we considered here are not always correct, it will be a good indicator to investigate errors factors more precisely using another instrument.

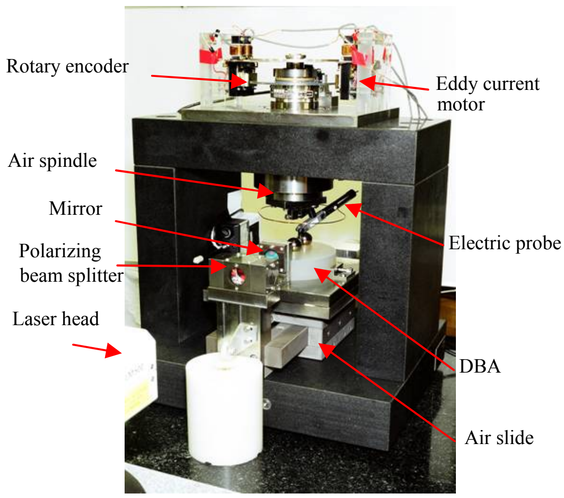
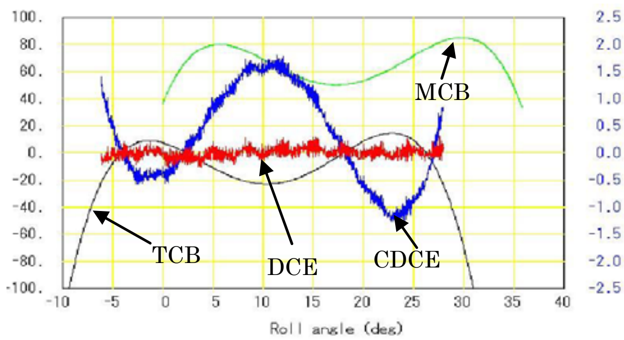


Fig. 3. Photo of the DBA calibration instrument



TCB: Theoretical Camel Back curve, MCB: Measured Camel Back curve
DCE: Deviation Curve for Evaluation, CDCE: Corrected Deviation Curve for Evaluation

Fig. 4. An example of a measurement of the DBA by a gear chcker

3. MULTI BALL ARTIFACTS

We have developed the Multi Ball Artifact (MBA) for only evaluating the pitch measurement performance of the GMIs [3, 4]. The first prototype of the MBA is shown in Fig. 5. The MBA is composed of a combination of balls, a cylinder and a plane. The centre cylinder is surrounded by multiple balls on a base plane and is used as a reference axis of the gear. The cylinder and balls are fixed by magnetic force. The plane is made from low expansion grass material. The concept of the first MBA is an easy assembling with a kinematic fixture and a low cost manufacturing.

The second MBA is shown in Fig. 6. The balls on the outer circumference (which are named pitch balls) are assumed to act as gear teeth. The ball at the center (which is named centering ball) is used to set a reference axis and the reference axis is assumed to a center axis of the gear. Pitch balls are arranged on a curvic coupling (type: 24180-120V, manufactured by Okubo Gear Co., Ltd.) in contacting with both tooth flanks and the pitch balls are also in contact with a cylinder manufactured to be concentric with the centering ball. The curvic coupling is manufactured very precisely and is inexpensive. The concept of the second MBA is a low cost manufacturing.

The third MBA is shown in Fig. 7 and Fig. 8 shows the cross section view of the MBA. The base plane is made of NEXCERA® (low thermal expansion ceramics), therefore the MBA is robust to a thermal effect. The NEXCERA material is possible to be manufacture very fine surface with a small surface roughness.

And the third MBA is possible to evaluate not only pitch measurement but the profile measurement capability of the GMI. If we choose the two spheres include the centre sphere of the MBA, the two spheres of the MBA perform like the DBA. And we are possible freely to choose any outer spheres for evaluating the profile measurement capability of the instrument.

The characteristics of the MBAs are as follows,

1) The balls can be manufactured with a profile accuracy of several tens of nanometers; therefore, measurement with extremely small uncertainty can be expected.

2) The MBA can be manufactured from a material with a low thermal expansion coefficient. It is difficult to manufacture a gear artifact from such a material.

3) Commercial GMIs can measure the MBA without any special software because a virtual gear dimension can be built for the MBA.

4) The angular position of the center of the pitch ball around the reference axis is determined by measuring multiple points; therefore, the calibration result of pitch deviation is almost independent of the positioning error of the probe.

5) The tooth-profile-measuring accuracy for GMIs can be also evaluated by the MBA.

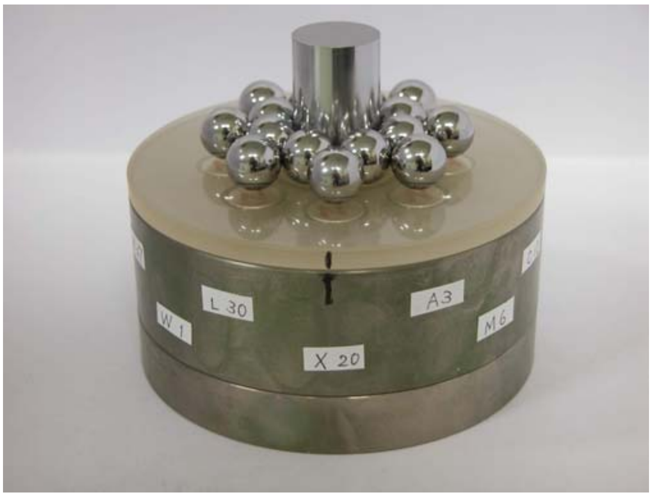


Fig. 5. Poto of the First MBA

Fig. 6. Photo of the Second MBA

Fig. 7. Photo of the Third MBA

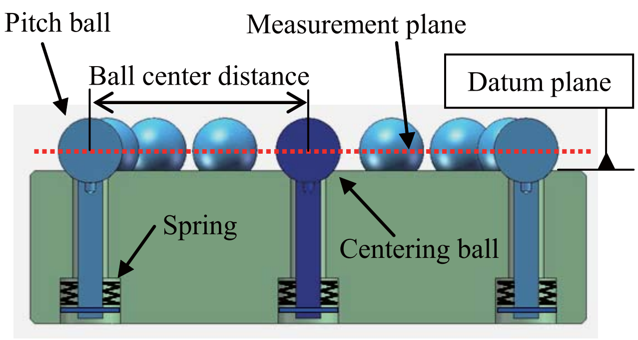


Fig. 8. Cross-section view of the third MBA

3. CALIBRATION OF MBA

For the profile evaluation, the important parameters of the MBA are the form of the ball and the length between the centre ball for making the datum and the surrounded ball. The ball form is very good. The sphericity (roundness) of the balls is usually less than 50 nm. The length between two balls has to be calibrated. A CMM with an interferometer and a rotary table is used for the calibration. The system is possible to calibrate the all lengths between the centre ball and the surrounding balls. Fig. 9 shows the calibration scene using the CMM with the interferometer. The rotary table helps for calibrating all lengths between the centre sphere and the surrounding balls.

For the pitch evaluation, the important parameter is an angle between adjacent balls. A CMM is used for the pitch calibration. The multi-orientation technique [5, 6] is applied to the measurement. Fig. 10 shows a photograph of a measurement setup. The rotary index table was placed on the CMM table and the MBA was clamped to the rotary index table. For the multiple-orientation technique, the MBA was set up in different orientations around the reference axis using the rotary index table. Fig.11 shows the positions of the MBA at each orientation. φ_j is the rotation angle of the rotary index table at the jth orientation. The rotary index table rotates at equal intervals such that

$$\varphi_j = -\frac{2\pi}{m}(j-1) \quad (j = 1, 2, \cdots, m), \tag{2}$$

where m is the total number of orientations. The angular position $T(\theta_i)$ was measured at each orientation and the angular pitch deviation $P(\theta_i)$ was calculated. The multiple-orientation technique eliminates the systematic error by averaging $P(\theta_i)$ for all orientations.

We denote the measurement curve of $P(\theta_i)$ at the jth orientation by $M(\theta_i, \varphi_j)$, which is the sum of $P(\theta_i)$, the systematic error $E(\theta_i+\varphi_j)$ and the non-systematic error E_{rand}, where E_{rand} is the component of the random errors of the CMM.

$$M(\theta_i, \varphi_j) = P(\theta_i) + E(\theta_i + \varphi_j) + E_{rand} \tag{3}$$

Here, we denote the mean of $M(\theta_i, \varphi_j)$ curves at all orientations by $\mu(\theta_i)$ as follows:

$$\begin{aligned}\mu(\theta_i) &= \frac{1}{m}\sum_{j=1}^{m} M(\theta_i, \varphi_j) \\ &= \frac{1}{m}\sum_{j=1}^{m}\{P(\theta_i) + E(\theta_i + \varphi_j) + E_{rand}\} \\ &= P(\theta_i) + E^{(m)}(\theta_i),\end{aligned} \tag{4}$$

where the expected value of E_{rand} is zero and $E^{(m)}(\theta_i)$ is a curve obtained from the sum of multiples of the mth-order Fourier components of $E(\theta_i)$. $E^{(m)}(\theta_i)$ is explained by the following law of the Fourier series: “An arbitrary curve with period 2π can be expressed by a Fourier series, and when m curves with a phase shift of $2\pi/m$ are averaged, the averaged curve can be written as the sum of integral multiples of the m^{th}-order Fourier components of the original curve.”

Fig. 9. Photo of the scene of the length calibration using a CMM with an interferometer

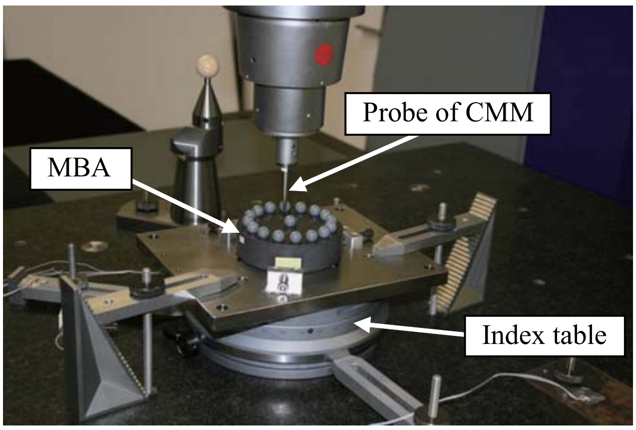


Fig. 10. Photo of the scene of the MBA pitch calibration by CMM

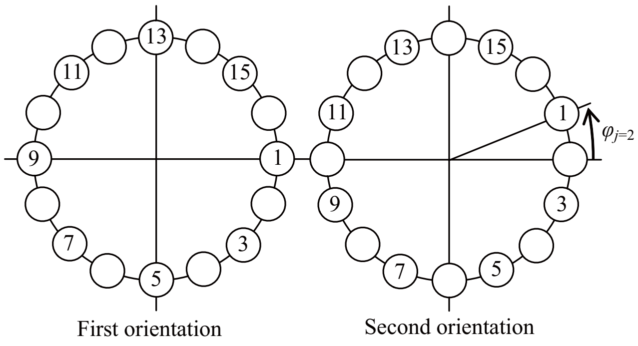


Fig. 11. Multi-orientation technique for gear pitch calibration

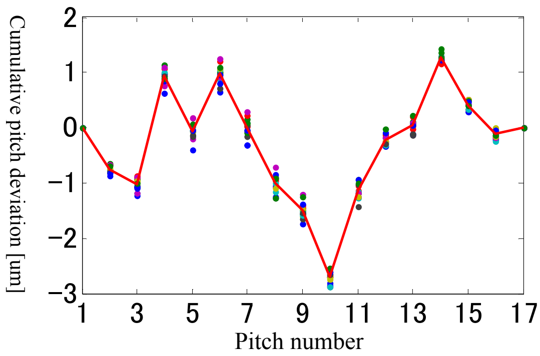


Fig. 12. Result of the cumulative pitch deviation (right flank)

Fig.12 shows the measurement result. We set the total number of orientations m to the total number of pitch balls N = 16. The dots show measured values at each orientation, and the line denotes the mean curve.

4. CONCLUSIONS

We proposed a novel artifact which is named Multi Ball Artifact (MBA) evaluating the profile and the pitch measurement performances of the GMI simultaneously. The MBA is composed of simple geometrical features, such as a plane, a ball and a cylinder. The geometrical features are manufactured with high accuracy and the manufacturing cost is low. And we proposed the calibration method of the MBA.

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