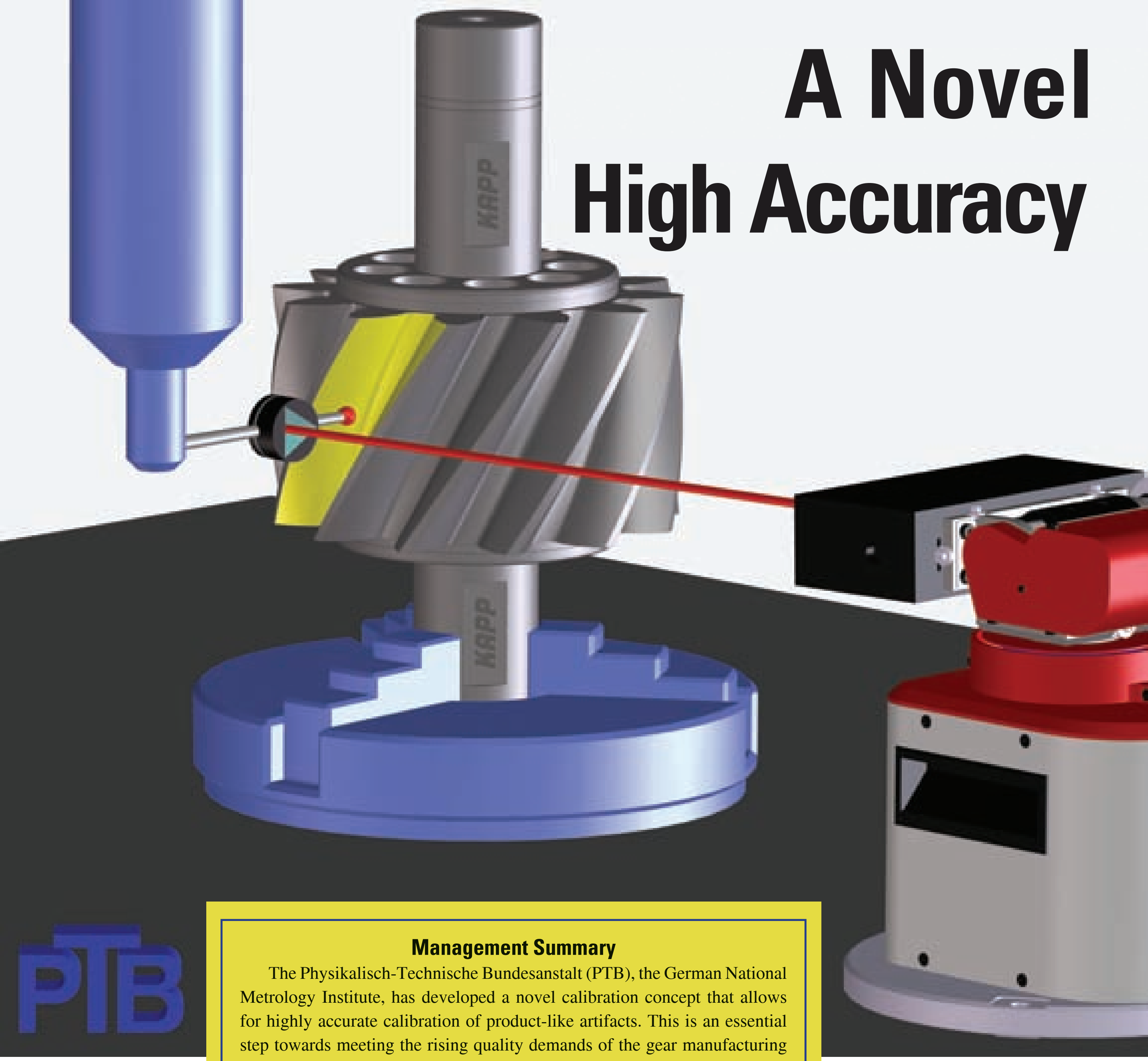
A Novel High Accuracy



Management Summary

The Physikalisch-Technische Bundesanstalt (PTB), the German National Metrology Institute, has developed a novel calibration concept that allows for highly accurate calibration of product-like artifacts. This is an essential step towards meeting the rising quality demands of the gear manufacturing industry by reducing the current calibration uncertainty of gear artifacts.

Recent national and international standards, such as AGMA and ISO, require gear manufacturers to account for measurement uncertainty. Accounting for it, gear manufacturers actually reduce their manufacturing tolerances from those specified on their prints. Consequently, they need highly accurate calibrations to make the uncertainty as small as possible, making their manufacturing tolerances as large as possible.

The measurement setup described is based on a coordinate measuring machine (CMM) equipped with a high-precision rotary table, a tracking interferometer (TI) for reading distance information and certified evaluation software. Both the measuring strategy for the complete measuring process and the reference algorithms, which provide a basis for a software test, were developed by PTB. Results on an involute profile artifact show that the measurement uncertainty of the new concept meets the high requirements.

Concept for Gear Calibration

By

Frank Härtig
Christian Keck
Karin Kniel
Heinrich Iven Schwenke
Franz Wäldele
Klaus Wendt

Introduction

Gear measurement tasks often require exceptionally high measurement accuracies. Today, specified tolerances for high quality gears often lie in the range of the uncertainty of the measurements. In these cases the quality of the products cannot reliably be assured (Ref. 1). A large part of the measurement uncertainties in industry can be attributed to the lack of highly accurate calibrated artifacts that embody the complex shape of industrial gears. Currently, the shapes of the national reference artifacts differ considerably from that of the industrial products. This makes the traceability via direct comparison with measurement results impossible. An increasing measurement uncertainty from the metrological institute down to the shop floor is the consequence (Ref. 2). Therefore, the PTB has developed a novel concept that can be used for the direct calibration of product-like artifacts.

Concept and Setup

All important measurement tasks of involute gears, like profile, lead and pitch measurements, are composed of a linear rotatory and a linear translatory motion. This special characteristic of gear kinematics can be used to minimize the influence of geometrical errors of machine guideways. The novel, high accuracy gear

Dr.-Ing. Frank Härtig *heads the work group for gear and thread metrology at the Physikalisch-Technische Bundesanstalt (PTB), the German National Institute of Metrology, located in Braunschweig, Germany. As group leader, he helps develop methods to determine and improve the measuring accuracy of national primary standards. Previously, he worked for several companies in coordinate measuring technology, specializing in gears, gearing tools and thread metrology. Härtig is also an active member of national and international standardization committees.*

Dipl.-Ing. Christian Keck *is investigating simulation and uncertainty assessment of coordinate measurements for PTB. An electrical engineer, he worked on the simulation of microelectronic devices and integrated circuits before joining the institute.*

Dipl.-Ing. Karin Kniel *works for PTB on coordinate measuring machines, laser tracking and gear metrology. A mechanical engineer, she helps develop methods to determine and improve the measuring accuracy of coordinate measuring machines.*

Dr.-Ing. Heinrich Iven Schwenke *is head of PTB's coordinate metrology section and this year became a corresponding member of the International Institution for Production Engineering Research (CIRP), which has its headquarters in Paris.*

Dr.-Ing. Franz Wäldele *is chief of the measuring instruments technology department at PTB. He holds 12 patents and is author of more than 130 technical papers. Wäldele is also a member of national and international standards committees pertaining to CMMs. Since 2003, he's been president of AUKOM e.V., the German association for training in coordinate metrology.*

Dr.-Ing. Klaus Wendt *works for PTB on new methods to determine and improve the measuring accuracy of optical 3-D coordinate measuring systems, especially in large-scale metrology. Before joining the institute, he worked in photogrammetry, the making of surveys and maps through the use of photographs. His doctorate is in geodesy, a field of applied mathematics concerned with measuring very large tracts of land.*

measuring device is based on this principle with the intention to achieve the most accurate measurement results (Ref. 3). The concept combines the flexibility of a CMM with the advantages of traditional measuring strategies. In the future this will allow calibration of 3-D product-like artifacts (Ref. 4) with almost the same accuracy as the 2-D national reference artifacts today. Figure 1 shows the different artifacts.

The new gear measuring device is based on four components: a high-precision, tactile Cartesian CMM, a rotary table, a tracking interferometer (TI) and certified evaluation software (see Fig. 2). The highly accurate rotary table is integrated into the machine table of the CMM. The geometrical errors of this rotary table are very small in comparison with those of a commercially available one. Furthermore, both the CMM and the rotary table are numerically corrected.

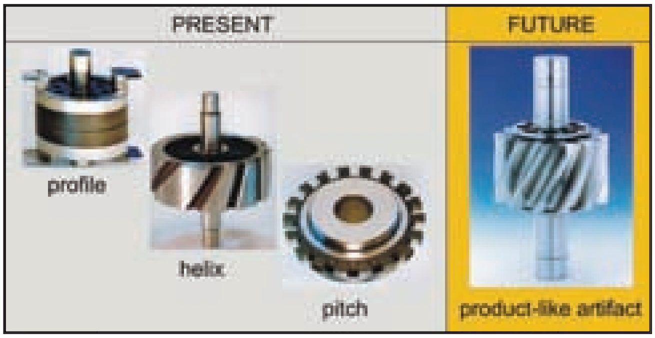
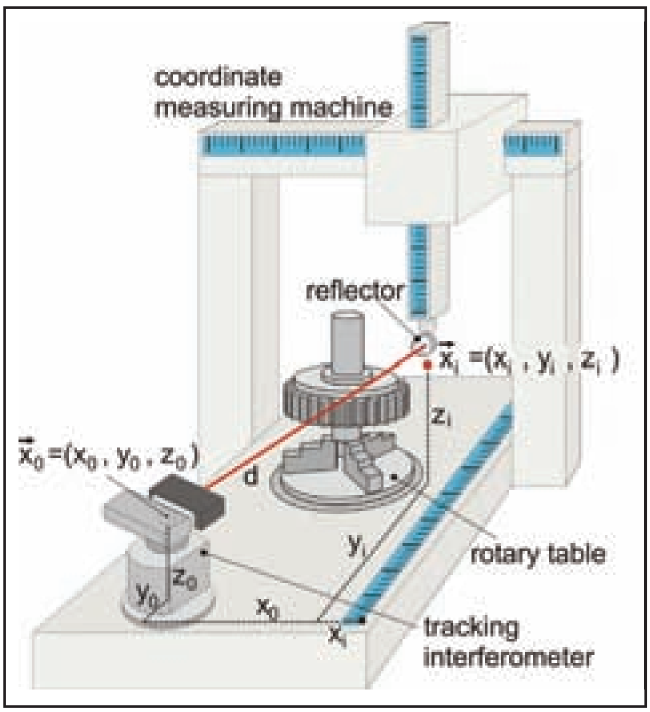


Figure 1—Current artifacts versus the new product-like artifact.



Component	Remark	Specification
CMM	MPE in µm (ISO 10360-2)	0.7+1.7*10^{-6}L
rotary table	angle position uncertainty in arc-sec.	0.08
	radial runout in µm	0.08
	axial runout in µm	0.03
TI	U(k = 2) in µm	0.07+2.3*10^{-7}L

Figure 2—The new gear measuring device (top) with technical specifications (bottom).

The TI is a development of PTB. Its laser beam follows a reflector mounted close to the probe tip. This allows evaluation of length information in the direction of the laser beam with interferometric accuracy.

Improved positions are obtained from a combination of the CMM and rotary table positions as read from the scales and of the distances measured by the tracking laser interferometer. All measurement information received from the machine components represents the measurement points with overdetermined numerical information. A patented algorithm (Ref. 3) is used to find improved positions. The temperature influence on the CMM and the TI is detected and corrected.

The measurement strategy and the evaluation algorithms for the complete measuring process were developed by PTB. The corresponding software was written in Java. For each single measuring point recorded in a static (non-scanning) mode, all readings of the components are triggered simultaneously by the CMM control.

Mathematical Background

The improved positions are calculated from the readings of the CMM scales and the distances measured by the interferometer on a point-by-point basis. This requires that the position $\vec{x}_0$ of the reference is known (see Fig. 2). To determine $\vec{x}_0$, the CMM has to be moved into at least four different positions ($\vec{x}_1$, . . . , $\vec{x}_4$) that must not lie on a common line, plane or sphere. In each CMM position $\vec{x}_i$, a measurement of the distance d_i is made. The unknown position $\vec{x}_0$ can be found by numerical minimization of the sum of squares errors:

$$\sum_i (|\vec{x}_i - \vec{x}_0| - d_i)^2 \longrightarrow \text{Min} \quad (1)$$

After the position of the TI has been determined, the actual measurement is performed. During a measurement, the probing system's signals, the machine scales and the interferometer length information are recorded simultaneously.

The calculation of the improved CMM position $\vec{x}'$ is performed as follows: The improved position $\vec{x}'$ and the position $\vec{x}$ read from the machine scales are assumed to have a difference of Δx. Their distances d and d' from the reference position differ by an offset Δd. The improved position is also related to the position $\vec{x}_0$ of the interferometer:

$$\vec{x}' = \vec{x} + \Delta\vec{x},\ d' = d + \Delta d,\ d' = |\vec{x}' - \vec{x}_0| \quad (2)$$

The coordinate and distance improvements can be found by mathematical optimization with a target function that puts a large weight on the distance measurements d' and a low weight on the position $\vec{x}'$. The reciprocal values of the estimated uncertainties of the CMM scale positions u_P and of the interferometric distance u_d are appropriate choices:

$$\frac{\Delta x^2}{u_P^2} + \frac{\Delta y^2}{u_P^2} + \frac{\Delta z^2}{u_P^2} + \frac{\Delta d^2}{u_d^2} \longrightarrow \text{Min} \quad (3)$$

In principle, the optimization can be performed by any numerical method. As no directional information is drawn from the TI measurement, reduction of the uncertainty of the position measurement is achieved only in the direction of the straight line connecting the probing system and the interferometer position.

If the uncertainty of the original position $\vec{x}$ is assumed to have the form of a sphere, the uncertainty of the improved position $\vec{x}'$ will take the form of an ellipsoid u_{res} during a profile measurement, as shown in Figure 3.

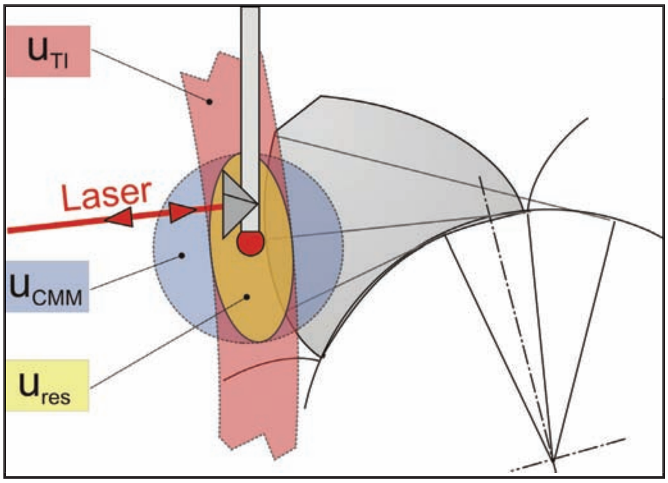


Figure 3—Reduction of the measurement uncertainty of the CMM u_{CMM} via additional length information (measurement uncertainty u_{TI}) to the resulting measurement uncertainty of the uncertainty ellipsoid u_{res}.

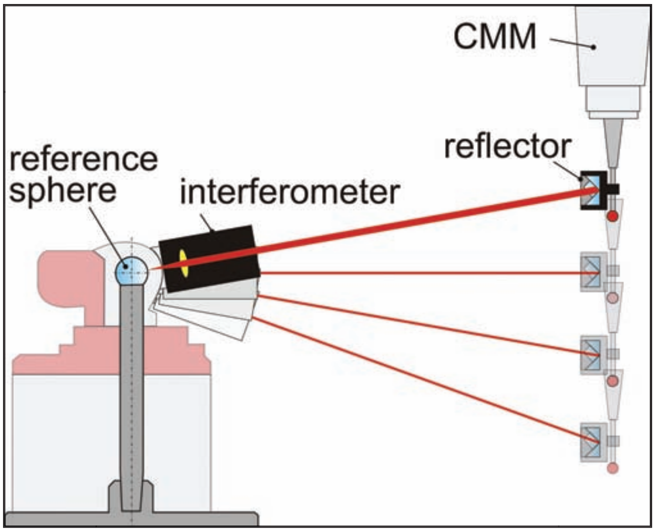


Figure 4—Tracking laser interferometer.

Tracking Laser Interferometer

The distance measurement uncertainty of the TI is the dominant uncertainty contributor of the system in the direction of the beam. The stability of the point of rotation is of especially great importance. As commercial laser trackers (Ref. 5) do not achieve distance measurement uncertainties in the submicron range, PTB has developed a new high-precision tracking interferometer. In its design, the gimbal-mounted interferometer moves around a fixed reference sphere serving only as the reference mirror for the interferometer (see Fig. 4). Due to this principle, radial and lateral deviations of the mechanical axes of rotation do not affect the measurement accuracy.

The accuracy of the TI length measurement depends significantly on the quality of the reference sphere surface and its unchanged position in space. To minimize its influences, the reference sphere has a form error of less than 30 nm. It is mounted on an invar stem to avoid any displacements due to thermal expansion. Atmospheric conditions, such as temperature, barometric pressure and relative humidity, are monitored to numerically correct the laser signal. As the TI is only 20 cm in diameter and 25 cm in height and has a weight of only 7 kg, it can be placed directly on the CMM table.

Reference Software

The new evaluation software allows evaluation of the measurement parameter of the modified flank geometries of product-like artifacts according to the definition of common gear evaluation standards and guidelines (Refs. 6, 7 and

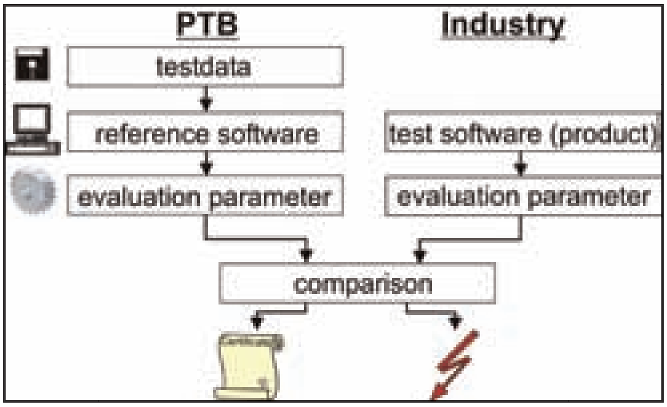


Figure 5—Certification of software algorithms.

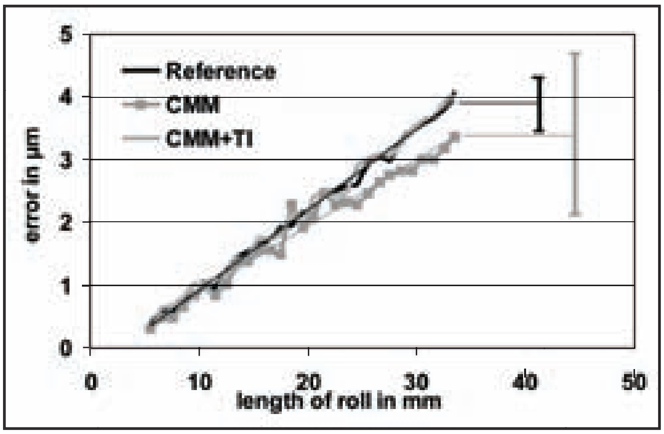


Figure 6—Results of an involute profile artifact.

8). Besides this application, the software can be used to compare the evaluation from PTB's reference software against the evaluations calculated by the industry. This allows the industry to certify its products. The principle of the software test can be seen in Figure 5.

Results

In order to verify the efficiency of the new approach on a gear involute profile artifact, comparison measurements were carried out. The high surface quality of the national reference profile artifact and measurement values with very small uncertainties provided excellent conditions for evaluating the new measuring method. The measurements were carried out according to the generative gearing principle.

The results in Figure 6 show very good agreement between the calibrated values of the artifact and the results of the new measuring device. Compared to measurement results obtained conventionally (CMM), it is demonstrated that the new method improves the measurement results considerably.

Conclusions and Outlook

PTB has developed a novel measuring device to calibrate gear artifacts. It is based on a high-precision Cartesian CMM with an integrated rotary table, a new tracking interferometer and certified software algorithms. Results show that the measurement uncertainty of the new gear measuring device complies with rising quality demands. Today it is possible to calibrate product-like gear artifacts.

References

1. Frazer, R.C. "A New Gear Calibration Facility for the UK's National Gear Metrology Laboratory," DETC2003/PTG-48106, *Proceedings of DETC '03*, ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Chicago, IL, Sept. 2–6, 2003.

2. Härtig, F., C. Keck, K. Kniel, H. Schwenke, F. Wäldele, and K. Wendt. "Development of a Novel Gear Measuring Device of High Accuracy," DETC2003/PTG-48105, *Proceedings of DETC '03*, ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Chicago, IL, Sept. 2–6, 2003.

3. Härtig, F., H. Schwenke, F. Wäldele and K. Wendt. Patent DE 10126753, "Verfahren zur Genauigkeitssteigerung von Koordinatenmessgeräten und Werkzeugmaschinen," Deutsches Patent- und Markennamt, Munich, Germany, Patent Granted June 2, 2001.

4. International Organization for Standardization, Standard ISO 18653:2003(E), *Gears—Evaluation of instruments for the measurement of individual gears*, ISO Copyright Office, Geneva, Switzerland, 2003.

5. Lau, K., R.J. Hocken, W.C. Haight. "Automatic laser tracking interferometer system for robot metrology," *Precision Engineering*, Vol. 8, No. 1, 1986, pp. 3–8.

6. Buschhoff, K., F. Härtig, S. Tian. "Zertifizierung von Verzahnungssoftware," VDI report 1618, VDI Verlag GmbH, Düsseldorf, Germany, 2001, pp. 149–158.

7. Verein Deutscher Ingenieure/Verband Der Elektrotechnik Elektronik Informationstechnik, VDI/VDE Guideline 2607, *Computer-aided evaluation of profile and helix measurement on cylindrical gears with involute profile*, 2000.

8. Deutsches Institut für Normung e. V., DIN Standard 3960, *Definitions, parameters and equations for involute cylindrical gears and gear pairs*, Beuth Verlag GmbH, Berlin, Germany, 1987.