XVI IMEKO World Congress
Measurement - Supports Science - Improves Technology - Protects Environment ... and Provides Employment - Now and in the Future
Vienna, AUSTRIA, 2000, September 25-28

HELICAL GEAR MEASUREMENT USING STRUCTURED LIGHT

J. Peters, G. Goch and A. Günther
BIBA-University Bremen
Hochschulring 20; D- 28359 Bremen, Germany

Abstract: Today, profiles of involute gears are measured with conventional or specialized coordinate measuring devices. The measuring speed of such instruments decrease with an increasing density of measuring points. Therefore, coordinate measuring devices often scan only a few lines of the gear surface. But these profiles represent only partially the functional behavior of the gear. This contribution describes a method, which measures the complete surface of a tooth in only a few seconds. A structured light pattern is directed towards the tooth. A CCD-camera records the stripes, deformed by the interaction between the surface and the light pattern. An algorithm transforms the registered graylevel patterns together with the system design data and the calibration information into the 3D-coordinates of the gear surface. At a measuring area of a few cm^2, the resolution amounts to about 1 µm. A 3D system calibration discussed in this paper aims at an improvement of the measuring uncertainty. Finally, first results of helical gear measurements are presented.

Keywords: gear measurement; helical gear; structured light; fringe projection; 3D calibration

1 INTRODUCTION

For gear measurements during their manufacturing processes, the fringe projection techniques offers several advantages in comparison to the conventional tactile measuring devices. A surface area can be registered by one measuring sequence. The 3D geometry is calculated from these stored data sets.

The whole optical system consists of a CCD camera and a fringe projector. The projector is build up using a commercially available digital micro mirror device, which is produced by Texas Instruments Inc for conventional video projection. This device enables various projection methods, especially phase correct measurements with sinusoidal fringe patterns.

An equipment for helical gear measurement is presented in this contribution. It concludes with first measurement results of helical gears.

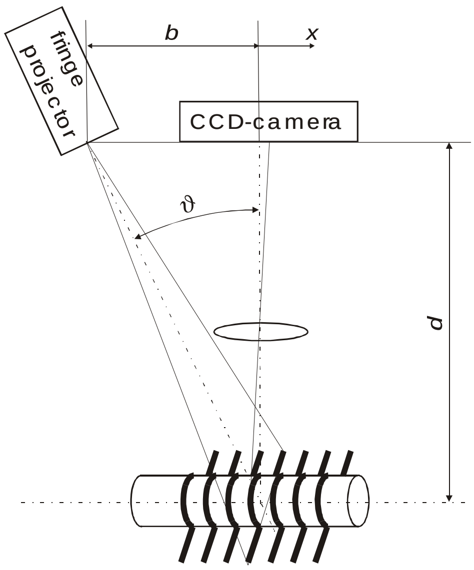

Figure 1. Principle of fringe projection

2 STRUCTURED ILLUMINATION

The basic principle of structured light illumination is a point by point triangulation.

Figure 1 shows the principle setup [BRE1993]. The fringe projector illuminates the object with a defined pattern. In accordance to the triangulation angle J, the fringes are deformed by the object, registered by the CCD camera and afterwards evaluated point by point. If there are singularities in the first derivative of the surface shape, it is not possible to achieve both, a high accuracy and a great measuring range. Therefore, the surface is illuminated with a sequence of fringe patterns, where e.g. each spatial fringe frequency is doubled. This method is called graycode [MAL1992]. The principle of graycode sequences is demonstrated in Figure 2. To each pixel of the CCD camera a light-dark sequence, coded in a 1-0 sequence, is assigned. This binary sequence

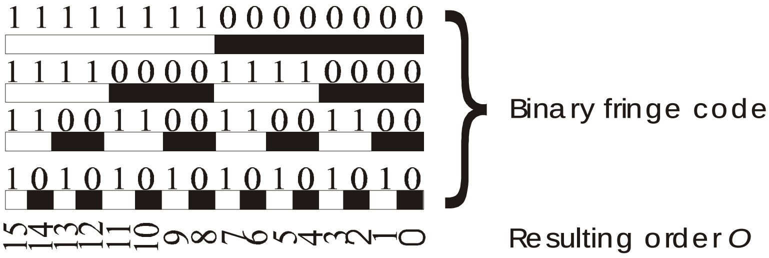

Figure 2. Example of graycode

corresponds to a resulting order *O.* This guarantees an assignment of the resulting order for the whole picture even in regions of unsteady derivatives of the object shape. Subsequently, the finest stripe pattern can be projected as a sinosiodal phase map. This leads to a better height resolution. To determine the phase at every pixel, the phase map must be projected at least three times, including a determined phase shift with respect to the surface. Four phase maps with a phase shift of 90 degree lead to a simple mathematical solution. For each pixel the phase can be calculated by the four obtained intensities using Equation 1 [OST1991]:

$$j = \arctan\left(\frac{I_2 - I_4}{I_1 - I_3}\right)$$

Combining the order O_{mess} of the fringe and the phase j_{mess} modulo 2π, the absolute phase is calculated. This information together with a reference information O_{ref} and j_{ref} together with the spatial wavelength Λ and the triangulation angle J leads to the height information *h*:

$$h = \frac{\left(O_{mess} - O_{ref} + \frac{O_{mess} - j_{ref}}{p}\right)\frac{A}{2}}{\tan u}$$

Equation 2 gives the formula for calculating the height in a similar form as suggested by Schmaltz [SCM1936].

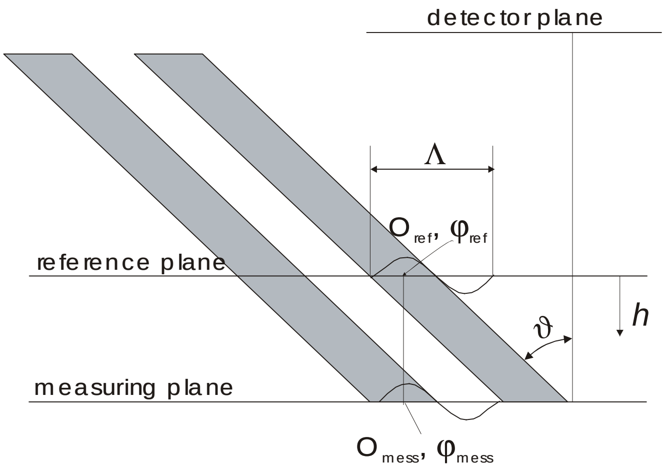

Figure 3. Reference plane and measuring plane

Figure 3 illustrates the reference and measuring plane. This figure shows the principle of triangulation and graycode. The spatial wavelength Λ and the triangulation angle J are measures for the difference between the fringe orders. If these geometrical conditions are known, the height *h* can be calculated. These quantities are determined by a calibration process. A simple 3D-calibration process is described in the next section.

3 SYSTEM CALIBRATION

One method to calibrate a fringe projector starts by recording the fringe orders and phases at one reference plane. In a next step, the height direction (axes) must be calibrated. This can be realized by evaluating the pattern changes obtained from a sample with a well defined height, one defined height step, for example in the order of one millimeter. The difficulty in this method is the production of a (not specularly reflecting) step of an exactly defined measure over a range of about 15 mm. The calibration is limited by the accuracy of the height step. The distance between two pixels in the detection plane corresponds through the lateral magnification of the objective to the object coordinates. The lateral calibration is performed by a grid, which is placed in the reference plane. If the used objective is telezentric, this lateral magnification is the same for all object points in the measuring volume.

4 GEAR MEASURING SYSTEM

The gear measuring system described in this contribution consists of a fringe projection system, as it is commercially available from GFMesstechnik Berlin, and a rotary table to position the individual gear teeth within the measurement volume [LU1998]. This setup is illustrated in Figure 4. The fringe projection system consists of a white light source, which is lead by a fiber to the measuring head. The light is directed to a micro mirror device, representing the central unit of this projection system. The mirrors can separately direct the light to the object or not. This results in illuminated and not illuminated object regions. The micro mirrors receive their control signal from a standard VGA card of a PC, allowing to project strait and adapted fringes to the object. The used telezentric objective guarantees an orthogonal projection to the CCD camera.

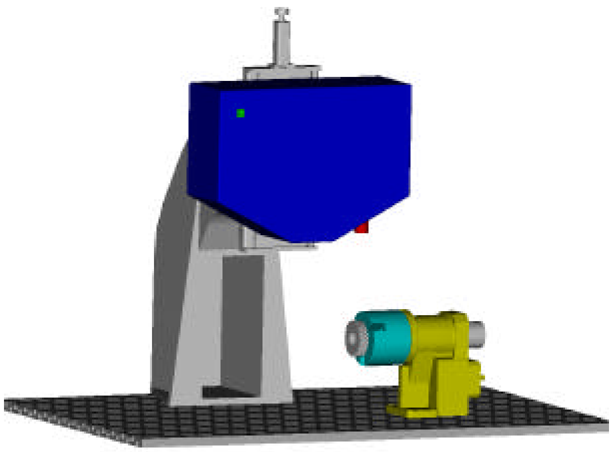

Figure 4. Gear Measurement Setup

Using the rotation unit, several teeth can be measured. The obtained flank data can be investigated separately for each tooth, leading to profile and lead deviations of the individual flank. Using the distance function approach described in [GTH1996, LOT2000], all measured data of all flanks can also be evaluated simultaneously. Thus, deviations concerning the whole gear wheel such as alignment and distortion as well as pitch and runout errors can be calculated. This leads to an approximation problem regarding 15 to 30 degrees of freedom [GTH1996].

5 MEASUREMENT RESULTS

Figure 5 shows the topographic results of 3D gear measurement. The contour plot is divided into several regions. The measurement of a tooth with one light source generates shade. The regions of shade can not be inspected without turning the measured object. The gear is illuminated from the right side. The left tooth flanks show good agreement with the expected coordinates, whereas the right tooth flanks show single peaks in this case, resulting from the shades. Therefore, the inspected tooth flank must be positioned by a rotary table perpendicularly to the incident light. Figure 6 shows a result for a rotated gear, showing less single peaks. The solid line in figure 7 represents a normal profile through the coordinates of Figure 6. The gear parameters are: module m=3; transverse pressure angle a_p=20°; tooth number z=34; helix angle b=30°. The equivalent base radius r_{bt} is 55.34 mm [ROT1989]. The involute resulting from this radius is plotted as stars. The measuring data and the theoretical curve coincide to a good degree, regarding the actual state of the project (less than 10 µm). The research work aims at a verified uncertainty of 2 to 4 µm.

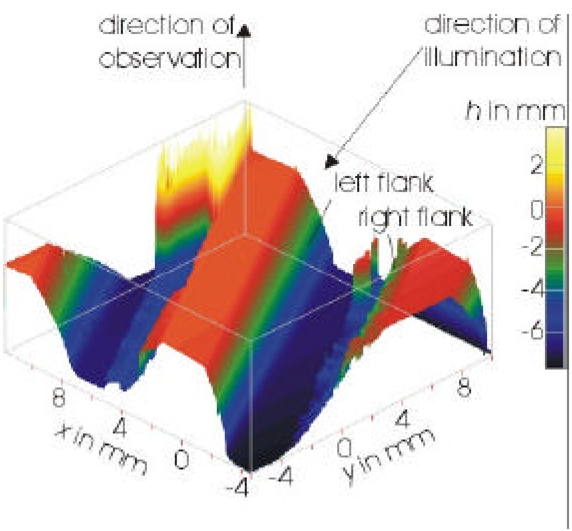

Figure 5. 3D Image of helical gear tooth

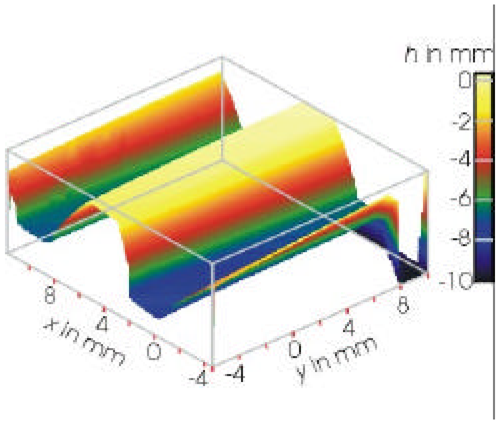

Figure 6. 3D Image of a turned helical gear

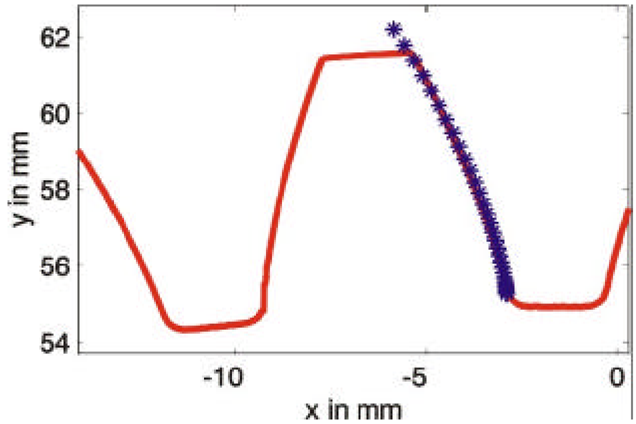

Figure 7. Normal profile through the 3D Image

6 CONCLUSION

In this contribution, a setup for helical gear measurement is described. The results show a good correlation between the measurement data of a master gear and the theoretical points. This result encourages future work on automated gear measurements. The major advantage of the fringe projection technique is the fast data acquisition of large areas. This leads to a new, area based, functional description of gears [GTH1996].

REFERENCES

[BRE1993] Breuckmann, B.: Bildverarbeitung und optische Meßtechnik in der industriellen Praxis. Franzis Verlag München 1993.

[GTH1996] Günther, A.: Flächenhafte Beschreibung und Ausrichtung von Zylinderrädern mit Evolventenprofil. Thesis submitted for a diploma, University of Ulm 1996.

[LOT2000] Lotze, W.: 3D-Messung von Zahnrädern - keine Kunst. Qualität und Zuverlässigkeit QZ, Vol. 45 (2000) 1, pp. 77-80.

[LU1998] Lu, G.; Wu, S.; Palmer, N.; Liu, H.: Application of Phase Shift Optical Triangulation to Precision Gear Gauging. Proceedings SPIE Vol. 3520, 1998, pp. 52-63.

[MAL1992] Malz, R.: Codierte Lichtstrukturen für 3D-Meßtechnik und Inspektion. PhD-Thesis University Stuttgart 1992.

[OST1991] Osten, W.: Digitale Verarbeitung und Auswertung von Interferenzbildern. Akademie Verlag Berlin 1991.

[ROT1989] Roth, K.: Zahnradtechnik. Band I Stirnradverzahnungen - Geometrische Grundlagen. Springer Verlag Berlin 1989.

[SCM1936] Schmaltz, G.: Technische Oberflächenkunde. Springer Verlag Berlin, Göttingen Heidelberg 1936.

AUTHORS: Dr.-Ing. Jörg PETERS; Prof. Dr.-Ing. Gert GOCH and Dipl.-Ing. Anke GÜNTHER: Bremen Institute of Industrial Technology and Applied Work Science (BIBA) at the University of Bremen, Hochschulring 20, 28359 Bremen, Phone Int. +49 421 218 5517, Fax Int. +49 421 218 5625
E-mail: pe@biba.uni-bremen.de