Preliminary measurement performance evaluation of a new white light interferometer for cylindrical surfaces

Armando Albertazzi Jr and Alex Dal Pont
Federal University of Santa Catarina, Metrology and Automation Laboratory, Cx Postal 5053, CEP 88 040-970, Florianópolis, SC, Brazil
E-mail: albertazzi@labmetro.ufsc.br

Abstract. This paper introduces a new design of a white light interferometer, suitable for measurement of cylindrical or quasi-cylindrical parts. A high precision 45° conical mirror is used to direct collimated light radially, making it possible to measure in true cylindrical coordinates. The image of the measurand, distorted by the conical mirror, is projected in a high resolution digital camera. A mapping algorithm is used to reconstruct the cylindrical geometry from the distorted image. The rest of the interferometer is quite similar to a conventional white light interferometer: A flat reference mirror is scanned through the measurement range while an algorithm is searching for the maximum contrast position of the interference pattern. The performance evaluation of a configuration suitable for measurement of external cylindrical surfaces is also presented in this paper. A master cylinder was used as reference. Uncertainties of about 1.0 µm were found at the present stage of development.

1. Introduction
White light interferometry has been used over a century in applications of practical interest. The main idea is to combine light from different arms of Michelson like interferometers and analyze the resulting pattern. Due to the small coherence length of white light, the interference pattern is only visible if the optical path difference of both arms is near zero. This principle has been successfully used as a high precision comparator to measure 3D shapes of either mirror like or rough surfaces. A reference mirror is scanned along the measurement range while the interference pattern is continuously acquired by a TV camera and an appropriate algorithm searches for the position of maximum contrast for each individual pixel on the image. At the end, a height map of a measurand is determined.

Most white light interferometry applications involve flat or almost flat surfaces measurements in either microscopic or macroscopic ranges. In this paper the design of a white light interferometer is extended to measure cylindrical surfaces. That opens new possibilities for applications of high interest in mechanical engineering.

2. White light interferometer for cylindrical parts
To measure cylindrical geometries, the basic white light interferometer is modified in the way presented in Figure 1. An near infrared LED is used as a non coherent light source with about 20 µm coherent length. The light is naturally expanded and split by a partial mirror in two components. One component goes through the partial mirror, is collimated, reaches a reference flat mirror and is
reflected back toward the partial mirror and then is imaged into a high resolution (1300 x 1030) digital camera. The other light component is reflected to the bottom by the partial mirror, is collimated and reaches a conical mirror. The conical mirror reflects the collimated light radially toward the cylindrical surface to be measured. The light is reflected back by the measured surface to the conical mirror and then propagates and is imaged into the camera. Interference patterns become visible if the optical path difference is smaller than the coherent length of the light source. A high precision motor moves the flat reference across the measurement range what produces equivalent changes in the radius of a virtual cylinder that scans the measurement volume. The peak of maximum contrast of the fringes represents the position where a virtual cylinder crosses the actual measured shape.

Figure 1. A modified white light interferometer with a conical mirror to measure cylindrical surfaces.

Figure 2 shows the effect of the reflection of a cylinder by a conical mirror. The cylindrical surface becomes a flat disc if imaged through a telecentric lens system. If the quality of the optical components and the alignment is good enough, the form deviation of the cylindrical surface is directly connected to the flatness error of the flat disc.

Figure 2. Effect of the reflection of a cylinder by a conical mirror.
3. Alignment and Calibration

A 22.5 mm diameter master cylinder was used as reference for both alignment and calibration. The form error of the master cylinder is better than ±0.5 µm. The mirrors and lens were carefully aligned to minimize the number of visible residual fringes. At the end, less than two fringes were visible.

The reference cylinder was then measured ten times. The apparent shape of the reference cylinder was computed from the mean value. Since the master cylinder was assumed to be the reference, this apparent shape was considered as the systematic error of the interferometer. This amount of systematic error was saved and used to correct all future measurements.

Data from ten repeated measurements were analyzed to estimate the typical random error component. The standard deviation was separately computed for each measured point on the cylindrical surface. A typical $\chi^2$ distribution was obtained for the standard deviation. The most frequent value was 0.11 µm and 95% of the values were smaller than 0.27 µm.

Other error sources were analyzed and their contributions are presented in Table 1. The type A component (standard deviation) and the master cylinder uncertainty were the most significant error sources. The expanded uncertainty was estimated with 95% confidence level to be about 1.0 µm.

| Symbol | Uncertainty source | Value | Distribution | Divider | $u$ | $v$ |
|--------|--------------------|-------|--------------|---------|-----|-----|
| $u_A$  | Type A (standard deviation) | 0.27 µm | normal | 1 | 0.27 µm | 9 |
| $u_{SE}$ | Systematic error uncertainty | 0.09 µm | normal | 1 | 0.09 µm | ∞ |
| $u_{Cu}$ | Master cylinder uncertainty | 0.50 µm | rectangular | $\sqrt{3}$ | 0.29 µm | ∞ |
| $u_C$  | Combined uncertainty | | normal | | 0.41 µm | 9 |
| $U_{95%}$ | Expanded uncertainty | | normal | $k = 2.325$ | 0.95 µm | |

4. Measurement examples

The interferometer has been successfully applied to measure gas compressor pistons. At the present stage, the alignment requires about 15 minutes. It starts with a coarse alignment trying to make the camera’s image uniformly illuminated. Then, by continuously subtracting two subsequent frames, it is possible to see lines that are equivalent to interferometric fringes that guide the fine alignment.

shows two measurement examples. The left part demonstrates that it is possible to measure stepped geometries. The right part is an exaggerated representation of the geometric errors of a gas compressor piston. No surface preparation was needed in any case. The scanning is typically from three to five minutes for each case. Two sections of this piston are shown in Figure 4.

Figure 3. Measurement examples of gas compressor pistons.
5. Conclusions
A new design of a white light interferometer is presented and preliminarily evaluated in this paper. The use of a conical mirror makes it possible to measure in true cylindrical coordinates. That configuration opens possibilities for new applications of high interest in mechanical engineering such as wear measurement in cylindrical surfaces. Either continuous or stepped cylindrical surfaces can be measured. The uncertainty achieved at this stage of development is about 1.0 µm. The authors believe that improvements in the scanning mechanism and the use of a better reference cylinder can reduce the expanded uncertainty to something below 0.3 µm. Current developments efforts are focused in the measurement of inner cylindrical geometries and development of algorithms for wear measurement.

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