A RADIAL WHITE LIGHT INTERFEROMETER FOR MEASUREMENT OF CYLINDRICAL GEOMETRIES

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Abstract

This work presents a radial white light interferometer developed for non contact measurement of cylindrical parts. The system uses an innovative radial interferometer of non coherent light, enabling the measurement of a whole cylindrical area without any circular movement of the part. The system is fully automated and, as the measurement is performed over an area and not over a line, a few vertical steps are enough to evaluate the whole form of internal or external cylinders. Up to 300.000 points can be measured in each acquisition, making possible an in depth analysis of the cylindrical geometry. Dedicated software process the clouds of points and calculate parameters as circularity in each section, straightness of boundaries, cilindricity, etc. The measurement of the part can be done also by comparison with a standard or by comparison with the part itself, for example, in the evaluation of wear and loss of material during test of products. The part is measured before and after running a test and the results can be compared and several parameters calculated. The calibration of the system defined an uncertainty of ±0,002 mm for absolute measurements and ±0,001 mm for differential measurements.

Keywords: White Light Interferometry, Precision Engineering, Dimensional Metrology

1. INTRODUCTION

White light interferometry has been extensively used for profiling of technical parts. It combines the high sensitivity of interferometers and the ability to perform absolute height measurements. Parts with lateral sizes ranging from few micrometers to over 100 mm can be measured. It is possible to achieve height resolution better than one nanometer and measurement ranges up to several millimeters, what makes this technique excellent for industrial applications concerning geometric quality control. Several commercial systems using this measurement principle are already available on the market.

A typical setup for white light interferometer is a Michelson like configuration. Light from a low coherent light source is collimated and directed to a partial mirror. Part of the light is directed to a reference surface, usually a high quality mirror, and is reflected back to the imaging device. Light is also directed to the object to be measured and is reflected back to the imaging device and it is combined with the light reflected by the reference surface. An interference pattern is only visible for those points where the optical path difference is smaller than the coherence length of the light source. The loci of the points where the interference patter is visible is a contour line for a given height. By moving the part to be measured or the reference mirror it is possible to scan the entire surface. An algorithm is used to find the position of maximum contrast of the interference patter for each pixel of the image and to assign a height value.

White light interferometers usually are naturally used to make measurements in rectangular coordinates. X and Y are associated with the lateral dimensions of the image and Z to the heights. In this paper the authors extends white light interferometry to measure in cylindrical coordinates. A high precision 45º conical mirror is used for both illuminate cylindrical parts and to image the resulting interference pattern into a CCD camera. This configuration opens possibilities for measuring high precision cylindrical or almost cylindrical parts. Either continuous or stepwise surfaces can be measured. The measurement principle, practical considerations and performance results are presented here as well few applications of practical interest. The system was developed at the Federal University of Santa Catarina in partnership with the company Photonita – Photonical Instruments for Technical Application Limited.

2. A RADIAL WHITE-LIGHT INTERFEROMETER

45° conical mirrors have some interesting optical properties. They can be used to optically transform rectangular coordinates into cylindrical coordinates. Collimated light propagating in Z direction is reflected by the conical mirror to propagate in radial direction, as shows Fig. 1. If a cylinder is aligned to the axis of the conical mirror its image reflected in a 45° conical mirror is transformed in such a way that it is seen as a flat disc. If the observer is located in the infinity or a telecentric optical system is used, and if the alignment and mirror geometry are ideal, a perfect cylinder is transformed into a perfect flat disc. If the quality of the optical components and the alignment is good enough, the form deviations of the cylindrical surface is directly connected to flatness errors of the flat disc.

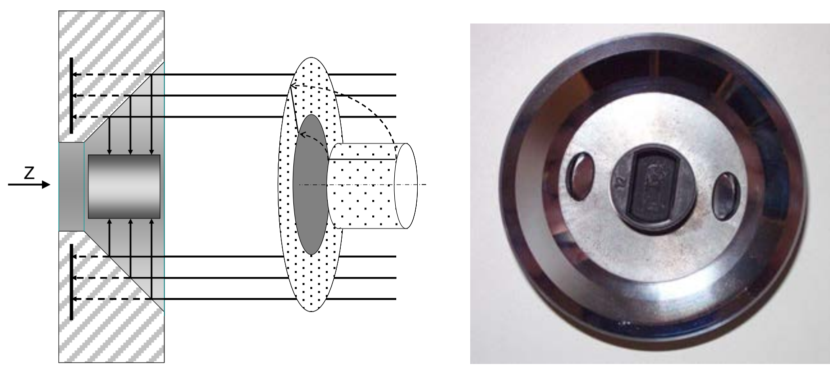

Figure 1 - Reflection of a cylinder by a conical mirror: cylindrical surfaces become flat discs

To measure in cylindrical coordinates the white light interferometer is modified in the way presented in Fig. 2. A near infrared ultra-bright 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. The first 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 second light component is reflected to the bottom of the figure by the partial mirror, is collimated and reaches a 45° conical mirror. The conical mirror reflects the collimated light radially toward the cylindrical surface to be measured, located inside the conical mirror. The light is reflected back by the measured surface to the conical mirror and then propagates and is imaged into the camera. Unlike most white light interferometers the collimating lens are placed after the partial mirror since a larger clear aperture was needed for the image of the measured cylinder measured by the conical mirror. Both collimating lens are similar to minimize the optical aberration differences between the two arms of the interferometer. The outer diameter of the 45° conical mirror is about 100 mm and was designed to fit the set of diameters and heights of the cylindrical pieces to be measured. It was manufactured in aluminium with an ultra-precision turning machine with a diamond tool.

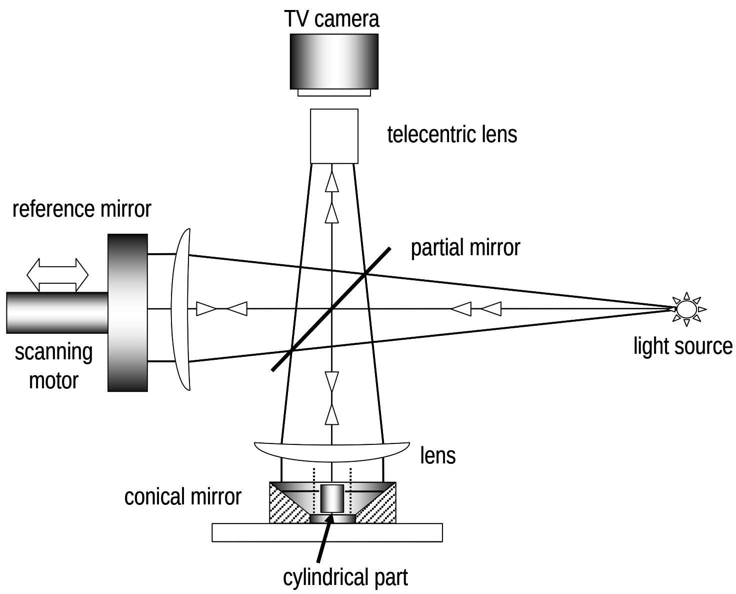

Figure 2 - Modified white light interferometer to measure in cylindrical coordinates

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 mirror across the measurement range what produces equivalent changes in the radius of a virtual cylinder that scans the cylindrical measurement volume. The peak of maximum contrast of the fringes is searched by the software for each pixel of the image and represents the heights of the flat disc what is equivalent to the radius where a virtual cylinder crosses the actual measured shape. So, the measured heights are converted to radius and the actual 3D surface is reconstructed from cylindrical coordinates.

A 22.5 mm diameter master cylinder was used as reference for both alignment and calibration. The master cylinder has an expanded uncertainty estimated as ± 0.5 µm. The position of mirrors and lens were carefully aligned in such a way to minimize the number of visible remaining fringes. At the end, less than one residual fringe was visible. The reference cylinder was measured ten times. The mean apparent shape of the reference cylinder was computed from the mean value for each measured point. Since the master cylinder was assumed to be the reference, the deviation founded was considered as systematic error. The idea is to compensate this systematic component in any 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 normal distribution was obtained for the standard deviation with most frequent value of 0,11 µm and 95% of the values smaller than 0,27 µm. Other error sources were analyzed and 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.

Table 1 – Uncertainty budget for cylindrical shape measurement

Symbol	Uncertainty source	Value [µm]	Distribution	Divider	u [µm]	v
u_A	Type A (standard deviation)	0,27	normal	1	0,27	9
u_{SE}	Systematic error uncertainty	0,09	normal	1	0,09	inf
u_{Cil}	Master cylinder uncertainty	0,5	rectangular	$\sqrt{3}$	0,29	inf
u_C	Combined uncertainty		normal		0,41	9
$U_{95\%}$	Expanded uncertainty		normal	k = 2,325	0,95	

4. DIMENSIONAL AND FORM ERROR MEASURUMENT OF CYLINDRICAL PARTS

With this optical setup the radial interferometer was applied to the measurement of pistons of gas compressors. The objective was to measure the cilindricity of the pistons before and after a running cycle, in order to evaluate the loss of material during this cycle. The measurement was done by comparison with the master cylinder used in the calibration process, and the results can be seen on the next figures.

Figure 3 shows the reconstructed geometry of the piston with about 300.000 points measured. The software has powerful tools to process these points and extract geometric parameters as circularity, straightness and diameter of the measured part. From the cloud of points it is possible to visualize (pan, zoom and rotation) the amplified error geometry of the piston and to analyze both radial and axial sections.

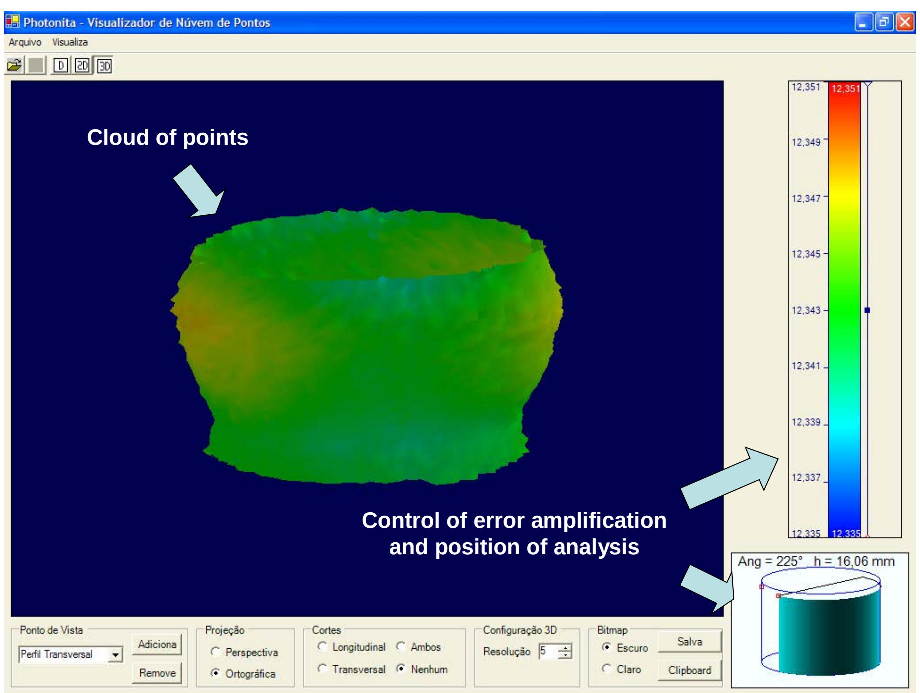

Figure 4 – Measurement software and dimensional analysis performed on the clouds of points

From the points measured on the surface of the piston the geometrical parameters are extracted to analyze the cilindricity of the pistons. Circularity at any radial section and straightness at any axial section are measured and displayed at standard graphical reports. The height of the circularity evaluation and the angle of the straightness evaluation are graphically or numerically selected, as shown at figure 4. Figure 5 shows the reports of circularity and straightness obtained from the processing of the measured point with the radial interferometer.

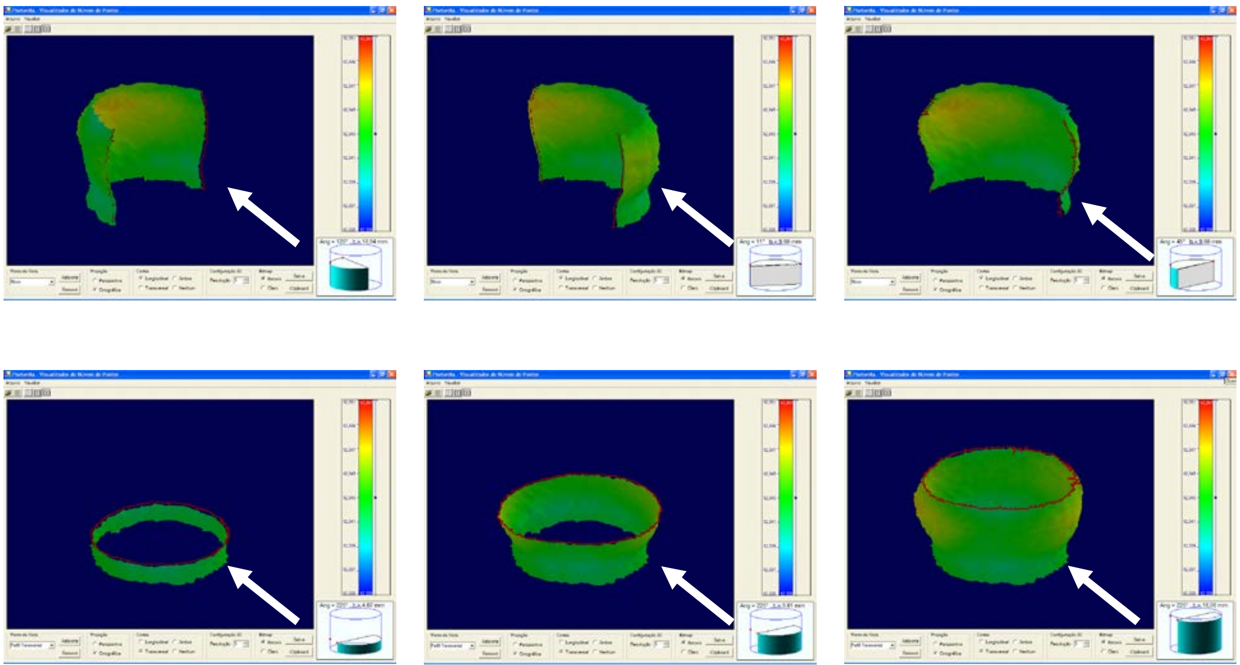

Figure 4 – Selection of position to analyse straightness and circularity on the piston surface

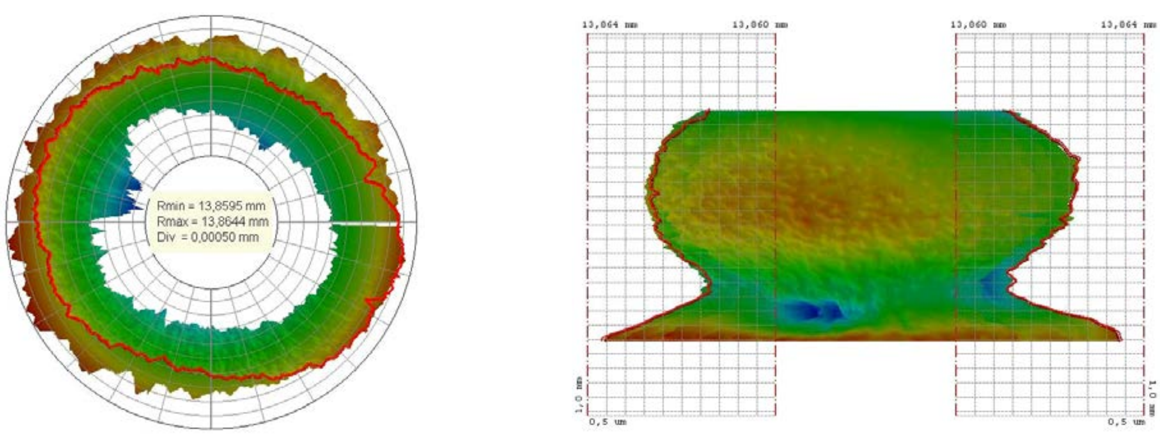

Figure 5 – Circularity and Straightness measurements at the piston with the radial white light interferometer

4. CONCLUSIONS

The dimensional and form measurements of cylindrical parts using classical contact measurement systems have some operational and metrological limitations. The measurement is a time consuming operation because the necessity of mechanical alignments and movements of the workpiece and/or contact probe. As the system scans a line at a fixed height each time, it is necessary to make several vertical steps to measure the whole shaft or hole. These operational limitations motivate the users to evaluate the cylindricity with a few measurements and, as a consequence, valuable information about the geometry of the parts remains unknown.

This paper introduced 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 bend the collimated light to radial direction, making it possible to measure in true cylindrical coordinates. The image of the measurand, distorted by the conical mirror, is projected on a high resolution digital camera. A mapping algorithm is used to reconstruct the cylindrical geometry from the distorted image. The remaining of the interferometer is quite similar to a conventional white light interferometer, where 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 external cylindrical surfaces, is also presented in this paper. A master cylinder was used as reference. Uncertainties of about 1 μm were found at the present stage of the interferometer. Recent tests and optimizations have been performed on the system and preliminary results are indicating an repeatability of ± 0,2 μm. There was not time enough to these tests be included in this paper but they will be reported in future works. With this setup the system was applied to the measurement of pistons of gas compressors with very good results, enabling a detailed geometric analysis of the measured part.

5. REFERENCES

1. Creath, K., *Phase measurement interferometry methods.* Progress in Optics XXVI, ed. E. Wolf, p. 349-442, 1988.
2. Dresel, T.; Häusler, G.; Venzke, H., *Three-dimensional sensing of rough surfaces by coherence radar.* Appl. Opt., v. 31, n. 7, p. 919-925, 1992.
3. De Groot, P.; Deck, L., *Three-dimensional imaging by sub-Nyquist sampling of white light interferograms.* Optics Letters. v. 18, n. 17, p.1462-1464, 1993.
4. Yatagai, T. *Recent progress in white-light interferometr*y, Proc. SPIE Vol. 2340, p. 338-345, Interferometry '94: New Techniques and Analysis in Optical Measurements; Malgorzata Kujawinska, Krzysztof Patorski; Eds., Dec 1994.
5. Groot P., Lega X. C., *Valve cone measurement using white light interference microscopy in a spherical measurement geometr*y, Optical Engineering 42(05), p. 1232-1237, Donald C. O'Shea; Ed., May 2003.