Roundness, angle, straightness and waviness measurements on recessed cones using scanning white-light interferometry

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1. Introduction

Valves are key components of the modern high-pressure fuel injection and hydraulic systems that power cars and trucks. The usual functional surfaces in a valve are the concave seat (a subregion of a conical surface) and a mating convex part (a subregion of a sphere or cone). Valve seat roundness tolerances are on the order of one micrometer or less, while cone angle tolerances are on the order of one degree or less. These tight tolerances require dedicated mechanical roundness profilers both on the factory floor and in the QC laboratory to validate the manufacturing process. Desirable improvements to valve metrology going forward include higher speed and lateral resolution, as well as challenging Gauge Repeatability and Reproducibility (GR&R) targets, all of which point towards optical solutions.[1]

We report in this paper a new experimental configuration of a scanning white-light interferometer that allows measuring the critical parameters of recessed valve seats. Typical surface profilers based on interference microscopy provide surface form and roughness by comparing the surface of interest to a plane datum. This is however not the ideal configuration to measure a conical surface, since the direction of illumination and observation is not normal to the surface. On the other hand, optical systems capable of generating a conformal conical wavefront with a sufficient lateral resolution over a large spectral range are difficult to design and manufacture and are by nature dedicated to discrete cone angles. We investigate here a flexible optical geometry that allows measuring a wide range of cone angles at various inspection diameters with a single optical system.

2. Measurement concept

The key idea is an interferometer that uses a datum point in place of the usual plane datum surface.[2] The measurement process brings this datum point at a location such that it becomes the center of a virtual mating sphere contacting the valve seat at the nominal seat diameter. The interferometric data allows measuring the distance between the sphere and the actual surface. Because the sphere and cone are tangent at the nominal seat diameter the direction normal to the cone surface corresponds to the sub-nm height resolution of interferometric measurements, providing the best possible functional metrology for the critical measurement of roundness at the seat. Adjusting the radius of the virtual mating sphere allows in principle to adapt the interferometer to any cone angle and seat diameter.

Figure 1a shows a conceptual instrument design. The core is a white-light Linnik interferometer. The optics on each leg of the interferometer are identical. They map a spherical object surface onto an intermediate image plane, which is imaged onto a camera by a telecentric relay. Chief rays in object space cross at the center of the entrance pupil. This location is the so-called datum point, the center of the virtual mating sphere to which the cone surface is locally compared. Practically, dedicated optics have been designed in order to fit inside an electroformed tube, as seen in Figure 1b, thus forming an endoscopic objective capable of reaching deeply recessed valve seats.

The reference leg optics include a concave spherical reference mirror that is concentric with the reference datum point. This defines a virtual spherical surface in object space where high-contrast fringes can be observed. A displacement of the reference leg optics over a few tens of μm forces the radius of this surface to change linearly, as if the spherical surface was inflating. Practically, interference data is recorded during such scans where the virtual sphere passes through the physical part surface. A large displacement of the reference leg optics is also used to offset the center of the scan, thus allowing to change the inspection diameter on a given part or to measure at the same inspection diameter for a part having a different included angle. In all cases, the region surrounding the nominal valve seat remains tangent to the virtual mating sphere. The introduction of large radius offsets may require refocusing the camera in some cases.

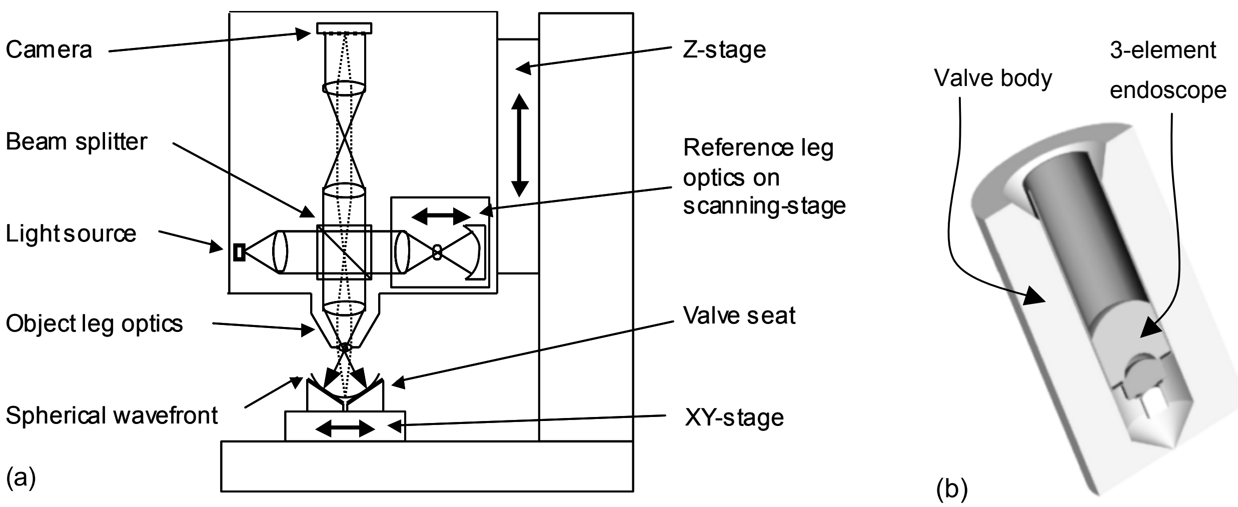

Figure 1 (a) Conceptual design of the optical gauge. (b) 3-element endoscope used both on the reference and object legs of the interferometer, shown here when measuring a deeply recessed valve seat.

3. Preliminary results of cone roundness and cone angle measurements

We studied the concepts outlined above on proof-of-concept breadboards. Data is captured during a scan of the reference leg. The raw height data obtained by processing of the interference data[3] looks like the top of a donut (it is a map of the distance from the conical surface to a virtual mating sphere). As an example, the band of data captured at a 2.7 mm inspection diameter on a 90° cone is typically on the order of 0.3 mm wide along the cone generatrix for a typical production surface finish. These data are transformed into a 3D representation of the object surface according to the projection defined in Figure 2a. A point P on the object maps to a point P' on the detector. A calibration using cones of different included angles establishes the relationship between the observation angle θ and the radius ρ at the detector. Another calibration with a sphere of know radius combined with the interferometric measurement of the conical surface allows the measurement of the distance r from the point datum to the object point P. Given these relationships a portion of the conical seat is reconstructed as shown in Figure 2b. A best-fit cone is then used to find the cone axis and included angle.

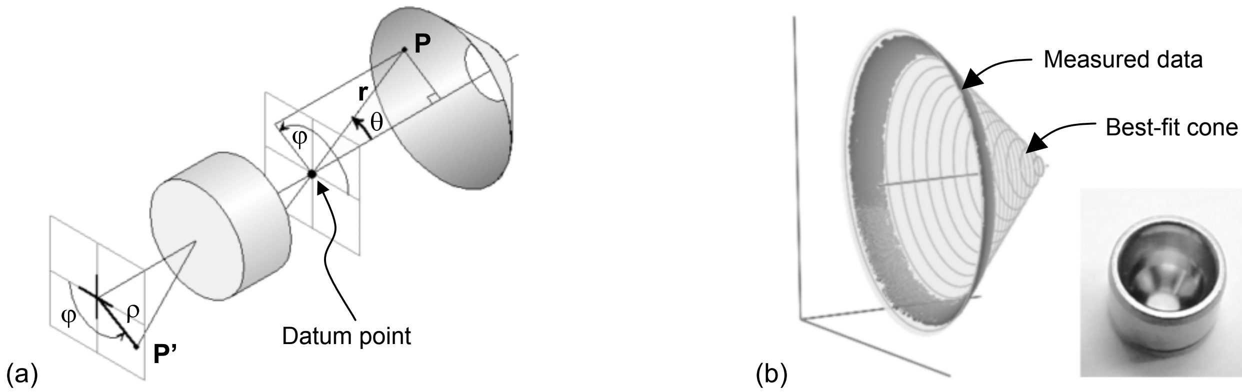

Figure 2 (a) Coordinate mapping of object point P onto detector point P’. (b) Reconstructed 3D surface and best-fit cone for a machined valve seat. A band of data about 0.35 mm wide is captured about the nominal seat inspection diameter.

Because the object surface is reconstructed in a coordinate system based on the datum point and the optical axis the best-fit surface indicates the amount of decentration and tip/tilt of the cone with respect to the interferometer. This information could be used on an automated instrument to readjust the cone position using the XYZ stages of Figure 1a if any of these parameters exceeds a predetermined threshold. This implies at most two measurements for a given part. By comparison, traditional tactile roundness profilers require a time-consuming iterative process for centering the part on the profiler spindle.

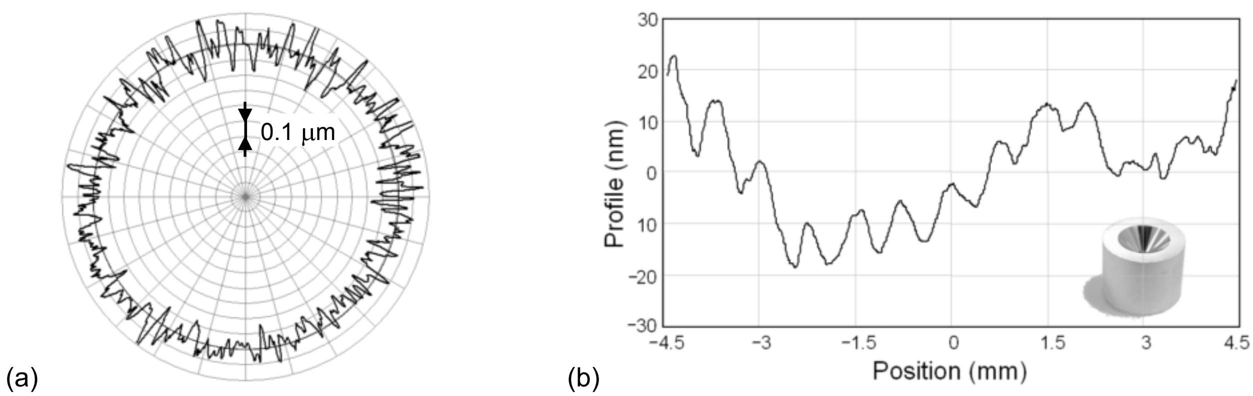

Figure 3 (a) Roundness profile at a specific seat diameter, extracted from the data in Figure2b. (b) Roundness profile plot for a diamond-turned conical seat. Note the surface oscillation on the order of 10 nanometers caused by the spindle motor poles of the diamond turning machine.

Subtraction of the best-fit cone from the surface data allows calculating the surface deviation along the local cone normal. One can then extract a roundness deviation profile at a location corresponding to a specific seat diameter. Different types of filters can be applied to the roundness profile to extract form, waviness and roughness. Additionally, profiles taken along the cone generatrix provide information about the lay pattern left by the machining process. An example roundness profile is shown in Figure 3a for the machined 90° valve seat shown in Figure 2b. The surface finish is fairly rough, as seen by the high-frequency surface deviation. The PV roundness deviation is about 0.4 μm for this particular part.

For calibration purposes we also manufactured diamond-turned conical surfaces. In this case the surface finish is fairly smooth compared to the mean wavelength of light. A roundness profile is shown in Figure 3b. The roundness error is smaller than 0.04 μm on this part. The resolution of the instrument also reveals a periodic 10-nm surface oscillation, which was found to correspond to the 12 poles of the motor driving the diamond-turning machine spindle.

A traditional metric in the automotive industry is the use of a GR&R study to validate the overall repeatability of a particular gauge. This typically consists in measuring a given set of parts multiple times, each part being loaded and unloaded between measurements. We ran such GR&R studies on conical seats having a surface finish similar to that of production parts and on smoother diamond-turned cones. The results for cone roundness and included angle are summarized in Table 1. We report here the standard deviation corresponding to the gauge repeatability. Usual practice requires the range defined by 5.15 x (standard deviation) to be smaller than 10% of the tolerance. The table shows that the performance of the proposed gauge is consistent with current submicron tolerances.

1-σ GR&R	Roundness	Included angle
Production-like cone	0.019 μm	0.012°
Diamond-turned cone	0.004 μm	0.001°

Table 1

4. Concluding remarks

The main benefits of the proposed gauge are those typically associated with optical profilers: non-contact collection of high-density 3D data instead of line traces (thus increasing the statistical significance of the data), as well as rapid data acquisition and repeatability/accuracy that compare favorably to that of mechanical profilers. Further work includes the study of alternative optical configurations,[4] for example systems that attach to traditional interference microscopes.

5. Acknowledgments

We wish to thank P. Drabarek, M. Lindner, M. Kraus, R. Mason and C. McNeely of Bosch GmbH for their collaboration. D. Griffith, J. Everett, D. Imrie and S. Fantone of Optikos Corporation designed and manufactured two generations of advanced probes and additional optical systems for this project.

6. References and notes

1 T. J. Dunn, "Optical metrology enables new generation of fuel injectors," Opt. & Phot. News, 28-33, June 2003.

2 P. de Groot and X. Colonna de Lega, "Valve cone measurement using white-light interference microscopy in a spherical measurement geometry," Opt. Eng., Vol. 42, No. 5, 1232-1237, 2003.

3 P. de Groot and L. Deck, "Surface profiling by analysis of white-light interferograms in the spatial frequency domain," J. Mod. Opt., Vol. 42, 389-401, 1995.

4 These cone measurement techniques are the topic of multiple US and foreign patents pending assigned to Zygo Corporation.