Valve cone measurement using white light interference microscopy in a spherical measurement geometry

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Abstract. We describe an interference microscope for valve cone angle, roundness, straightness, and waviness using scanning white light interferometry. Our unusual test geometry creates a spherical optical measurement surface centered at an optical datum point that represents the center of curvature of the mating valve needle or ball. A radial scan locates intersections of the measurement surface with respect to the datum point, and software reconstructs the conical sample surface by means of a calibrated mapping function. This flexible approach accommodates a wide range of cone angles and diameters without a change of optics. Experimental results show promising performance, including a 0.02-μm standard deviation for cone roundness, including sample removal and replacement.
[DOI: 10.1117/1.1565350]

Subject terms: interference microscope; white light interferometry; valve cone measurement; interferometers; optical instruments and equipment.

Paper MET-15 received Sep. 19, 2002; revised manuscript received Oct. 18, 2002; accepted for publication Oct. 18, 2002.

1 Introduction

Valves are a fundamental building block of high-pressure injection systems, pumps, and hydraulic actuators that fuel the engines of the transportation industry. Many of these valves require precision machining of interior conical surfaces, to which balls or needles mate to form an intermittent seal, often under pressures exceeding 1000 atmospheres. The quality of this seal is critical to clean, efficient operation of diesel and gasoline engines. Conical form is a high-priority metrology task, particularly roundness of the valve seats, which is the key to valve function as it relates closely to leakage. Many of these surfaces are recessed within narrow cylindrical bores.

Presently, most measurements on fuel system components are mechanical or tactile (stylus gages). There is strong motivation to transition to optical techniques for complex surface shapes such as torics, conics, and cylinders.[1–4] The key advantage of optics is the 3-D aspect of the surface measurement, as opposed to the linear trace of a mechanical stylus gage, as well as the speed and accuracy of the measurement. However, interior cones are difficult to measure optically, because of their unusual shape and surface texture, when compared to the more familiar optical testing samples such as mirrors, prisms, and lenses.

Interference microscopes most often compare surfaces to reference flats using conventional plane imaging to an electronic camera. Thus the measurement wavefront and coincident focal surface are both flat. Although this planar measurement geometry is sufficient for a wide variety of measurement tasks including those involving complex shapes, it is less than ideal for rapid evaluation of conical form parameters such as roundness of a valve seat.

It is natural to consider ways of altering the geometry of the optical measurement using, e.g., diffractive or refractive axicons, and employ an optical measurement technique compatible with rough surfaces.[5] This is not an easy task for a cone. For highest lateral resolution, the surface of best focus should match the measurement wavefront. Creating such a conical wavefront is incompatible with the normal focusing properties of the instrument, particularly if the measurement technique involves broadband illumination and therefore laterally and longitudinally achromatic optics. As a final requirement, it would clearly be desirable to have one set of optics accommodate multiple cone angles and valve seat diameters, so as to avoid a custom design for every application.

2 Spherical Optical Geometry

In our view, the key to simplifying the optical measurement is to look at the cone from the perspective of the mating needle or ball. For a wide variety of valve types, the valve seat is actually a fairly narrow annular region of the cone, similar to a pie plate with the bottom knocked out. Even when the mating part is a needle rather than a ball, the seal itself is usually a narrow contact area similar to what would be formed by a ball placed inside the valve cone. Thus we are most interested in how the cone surface deviates from the ideal as viewed by, e.g., an imaginary sphere nominally placed at the same position as the actual mating ball of the valve.

Our approach to the metrology of valve seats is an all-optical evaluation of the deviation of the conical and other complex valve shapes with respect to a sphere centered on an optical datum point located near the cone axis (U. S. and foreign patents pending). This turns out to be a more prac-

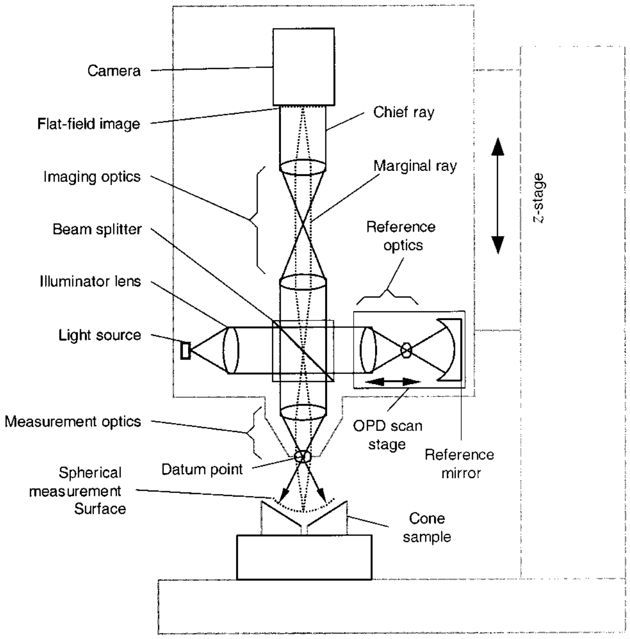

Fig. 1 Conceptual design of the proposed optical gage for measuring valve cones.

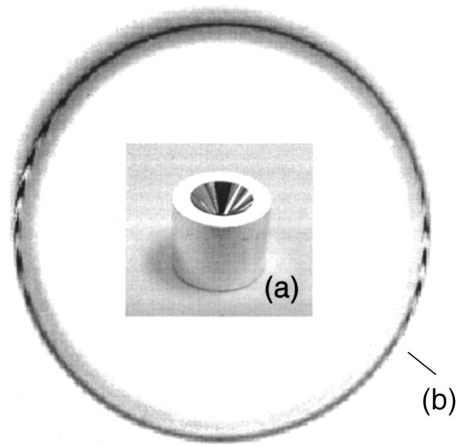

Fig. 2 (a) 5-mm-diam diamond-turned cone with a 90-deg included angle. (b) Experimental image of the cone in the proposed spherical geometry showing an intersection ring with interference fringes.

tical and realizable technique than creating a matching conical wavefront. A suitable arrangement of conventional refractive optics provides both a spherical wavefront and a spherical focus surface.

Figure 1 is a conceptual diagram of the essential features of our cone measurement system. This is a white light scanning interferometer, for which the localization of fringes about zero optical path length (OPD) allows one to determine the difference between a reference and a sample surface by two-beam interferometry even for machined surface finishes.[6,7] We use a Linnik geometry, in which the reference and measurement arms are matched as well as possible, to compensate for chromatic dispersion and residual aberrations. The sample surface is in this case a cone, while the reference surface is a sphere. The measurement optics are arranged so that the surface of best focus nominally matches the measurement surface, which is defined here as the spherical surface of zero OPD. The chief rays are orthogonal to this surface and intersect at a single point that serves as the reference datum for measurements of the cone geometry.

3 Data Acquisition and Analysis

Scanning the reference mirror and optics together mechanically varies the OPD of the interferometer. In the geometry of Fig. 1, this OPD scanning is equivalent to continuously varying the radius of the measurement surface. Using the principles of scanning white light interferometry, we detect as a function of radius the intersections of the measurement surface with the sample cone. Figure 2 gives experimental data from a diamond-turned cone that shows a narrow ring of interference fringes representing the intersection of the measurement surface with the cone at a specific measurement radius during the OPD scan. These data, acquired over a range of measurement surface radii, eventually lead to a complete form measurement within the narrow confines of the valve seat area, typically an annulus a few hundred microns in height and a full 360 deg around.

One of the important benefits of the measurement geometry is compatibility with a wide variety of cone angles and seat diameters. Figure 3 illustrates this benefit for two ex-

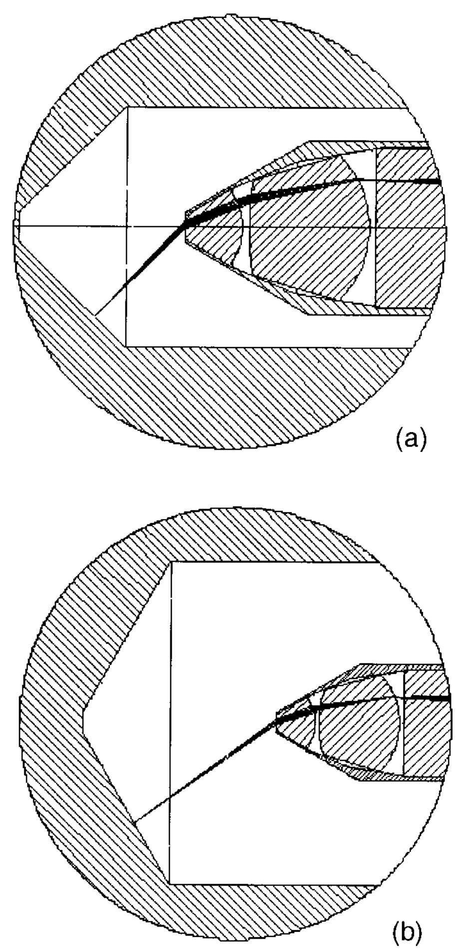

Fig. 3 (a) Measurement probe cross section with a 90-deg included angle cone in a 4-mm-diam bore. (b) Same measurement probe but with a 120-deg included angle cone in an 8-mm-diam bore.

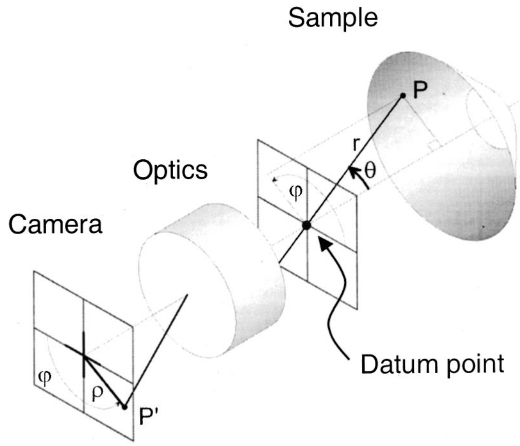

Fig. 4 Mapping of the spherical measurement geometry to the imaging plane of the camera.

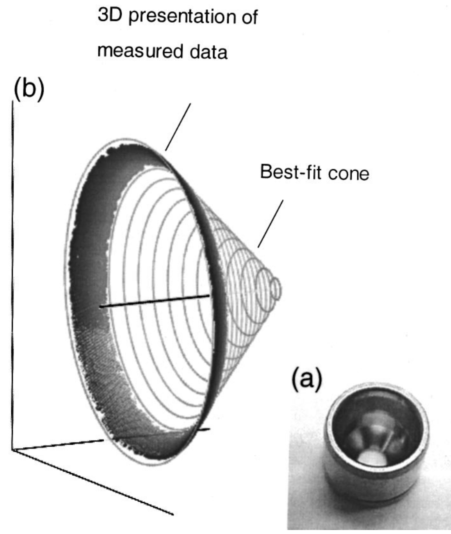

Fig. 5 (a) Sample similar to an actual valve cone. (b) Experimental data and best-fit cone.

ample cones and one of our optical designs for measurement probe. The upper drawing shows a narrow-bore cone with a typical 90-deg included angle, while the lower drawing shows the same probe measuring a flatter 120-deg cone in a larger bore.

As is illustrated in Fig. 4, the spherical measurement geometry maps into a flat-field camera image according to a coordinate transformation that can be as simple as

$$\rho = P\theta, \tag{1}$$

where ρ is the radius on the camera image with respect to a central datum point image and P is a scaling factor. Thus the magnification of the system is constantly changing during the scan of the measurement sphere, while the mapping of the ray angle θ onto the camera is fixed. This behavior is very different from the more common telecentric imaging, for which one seeks to maintain constant magnification for a range of object positions. The direct results from a measurement are therefore a collection of measured radii r as a function of the angle θ (calculated from ρ) and azimuthal angles φ.

The $r(\theta,\varphi)$ data provide directly the difference between the sample surface and a virtual spherical surface in contact with the sample. The form of the cone surface alone may be inferred by transforming the data from the r,ϕ,ζ coordinate system to a 3-D presentation in a more familiar x,y,z coordinate system using

$$x = r\sin(\theta)\cos(\varphi),$$

$$y = r\sin(\theta)\sin(\varphi), \tag{2}$$

$$z = -r\cos(\theta).$$

The next logical step is to apply a nonlinear least-squares fit of a best-fit theoretical cone surface having a specific cone angle, decenter, and tilt with respect to the instrument optical axis at the valve seat diameter. Figure 5 illustrates this fitting operation for an experimental dataset for a 3-mm-diam, 90-deg cone having a surface finish typical of some fuel injector valves, which are typically unpolished by design. The fit operation itself provides important information such as the cone angle. Figure 6 shows the residuals after subtraction of the best-fit surface and projection onto a flat plane. The residual plot reveals surface details such as machining marks and surface roughness, shown more clearly in the radial or straightness cross section of Fig. 7.

Figure 8 is a representation of the residual profile for a circular slice through the best-fit cone at a selected diameter value. The resulting roundness profile is a familiar format to users of stylus gages. This profile represents the surface deviation measured along the local surface normal. Equivalently, the roundness profile of Fig. 8 represents the deviation from a perfect fit of a perfectly round ball resting in the cone.

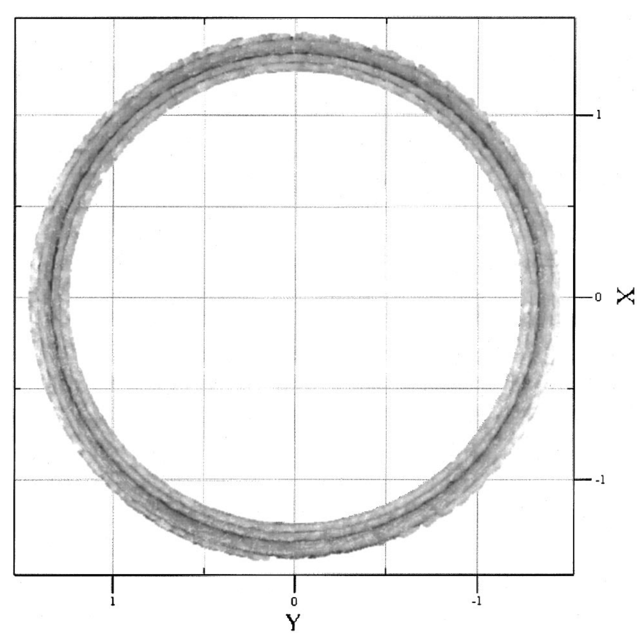

Fig. 6 Residual after best fit for data in Fig. 5(b).

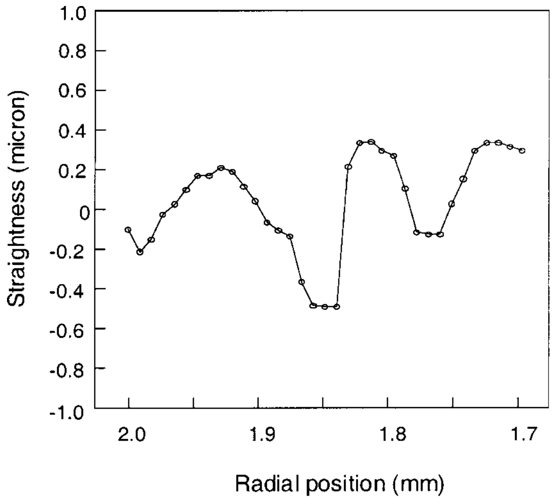

Fig. 7 Radial slice through the data shown in Fig. 6, showing the straightness profile.

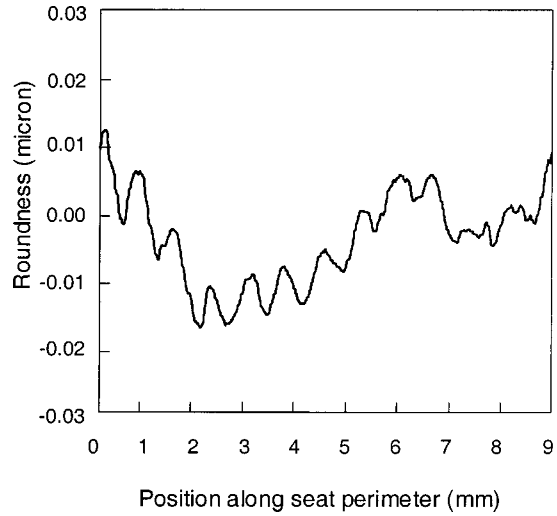

Fig. 9 Alternative roundness display, this time of a diamond-turned surface.

Figure 9 is an alternative representation of roundness, this time of the diamond-turned cone of Fig. 2. The profile shows periodic 0.01-μm-high lobes that are highly repeatable with part removal and replacement, and that follow the sample when the sample is rotated in its fixture. We confirmed with the manufacturer that these lobes are an expected result of the diamond-turning process when using a 12-pole spindle motor. Note that Fig. 9 has a very low noise level on the order of 1 nm.

4 Performance

Although it can be argued that the spherical measurement geometry is not perfectly matched to the conical surface shape of most valves, our approach already determines the key parameters of roundness, cone angle, and surface roughness along the valve seat with a repeatability that compares favorably to that of mechanical form metrology tools. This good performance is largely attributable the high data density of optical imaging. We acquire up to 50,000 data points during a 5-s data acquisition, typically with a lateral resolution of 10 μm over the entire valve seat region, facilitating a large amount of averaging for overall form parameters. System calibration relies on a known reference sphere to compensate for optical imperfections and a known conical surface to locate the datum point and calibrate for cone angle.

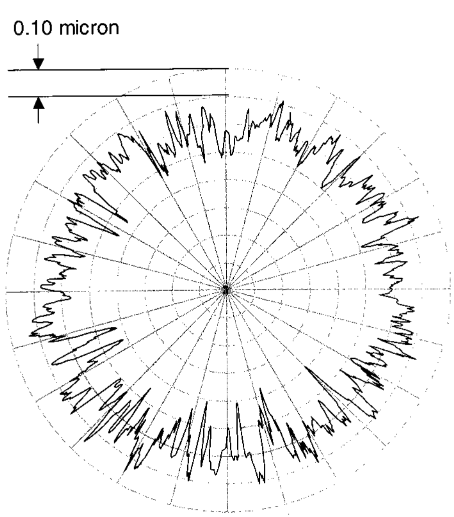

Fig. 8 Circular slice through the data given in Fig. 6, showing the roundness profile.

Table 1 Gage repeatability and reproducibility data for cone half angle, in degrees, for 20 cone samples having a surface form and finish similar to that of actual fuel injector valves.

Part #	Series 1	Series 2	Difference
1	44.902	44.913	−0.011
2	45.043	45.089	−0.047
3	45.058	45.053	0.005
4	44.968	44.964	0.004
5	45.011	45.005	0.006
6	45.068	45.064	0.004
7	44.889	44.891	−0.002
8	45.126	45.123	0.002
9	45.007	45.007	0.000
10	45.090	45.046	0.044
11	45.066	45.062	0.004
12	45.043	45.052	−0.009
13	45.096	45.099	−0.003
14	45.026	45.033	−0.008
15	44.964	44.972	−0.009
16	45.062	45.060	0.002
17	45.095	45.094	0.001
18	44.987	44.973	0.013
19	44.986	44.989	−0.003
20	45.099	45.079	0.020
		Range	0.0908
		St. Dev.	0.016

Table 2 Gage repeatability and reproducibility data for roundness, in microns, for 20 cone samples having a surface form and finish similar to that of actual fuel injector valves.

Part #	Series 1	Series 2	Difference
1	0.096	0.070	0.026
2	0.092	0.067	0.024
3	0.072	0.092	−0.020
4	0.092	0.099	−0.008
5	0.136	0.138	−0.002
6	0.215	0.260	−0.045
7	0.116	0.111	0.005
8	0.140	0.140	0.000
9	0.194	0.183	0.011
10	0.134	0.140	−0.006
11	0.098	0.136	−0.038
12	0.082	0.103	−0.021
13	0.207	0.214	−0.006
14	0.114	0.104	0.010
15	0.189	0.176	0.014
16	0.098	0.078	0.020
17	0.221	0.214	0.008
18	0.237	0.214	0.024
19	0.125	0.129	−0.004
20	0.255	0.253	0.002
		Range	0.071
		St. Dev.	0.019

Table 1 reports the results of a gage repeatability and reproducibility (GR & R) study of cone angle using 20 sample cones. (GR & R is a standard test used in industry.) A 10% gauge means that the measurement error due to both user and instrument is less than 10% of a max/min range tolerance with a confidence level of 99.0% (5.15 σ). These samples were generated for us by common machining techniques, but are not intended to reflect the current tolerances and production capabilities of any specific manufacturer of fuel injector valves. In this test, each of the 20 samples is measured in sequence, and then the sequence is repeated to determine the ability of the instrument to report the same results, including sample removal and replacement. The average standard deviation of 0.016 deg would be consistent with a $<10\%$ gage on a 1-deg tolerance on actual valve cones. Table 2 provides the results of a roundness GR and R study, showing 0.019 μm, which also would be consistent with a $<10\%$ gage on a 1-μm tolerance. A similar GR & R study with diamond-turned cones (see Figs. 2 and 9) shows $<10\%$ gage capability on a 0.3-μm tolerance for polished cones.

The 10-μm lateral resolution is sufficient for a simultaneous measurement of surface waviness up to a spatial frequency of 250 undulations per revolution (UPR). We also achieve a satisfactory 13% GR and R for a waviness tolerance of 1 μm on machined parts.

Although these preliminary results were achieved on an experimental laboratory setup on an air table, we expect the measurement to be quite robust in the presence of vibration and environmental changes. The range of height values is typically less than a few microns in the spherical geometry when the part is properly aligned with respect to the instrument optics, so the data acquisition time over which the measurement surface intersects the part is actually quite fast, much less than a second. The relative roundness and waveness values are also nearly independent of temperature-dependent parameters, such as the overall part size.

5 Concluding Remarks

These preliminary results show promising performance with a flexible measurement geometry for conical surfaces. Our next step will be to evaluate cost-effective methods of implementation of these ideas and verify these results on production fuel injectors. Some of these methods include alternative scan techniques, including the Lindner's intermediate image scan to preserve image focus, or vertically scanning the entire objective in a manner compatible with current practice in commerical interference microscopes.[8] Further, it would be of great interest to measure cone parameters with respect to datum surfaces defined, e.g., by the bore of the valve. This is an area of continued research.

Acknowledgments

We would like to thank Pawel Drabarek, Michael Lindner, Martin Kraus, Ron Mason, and Charles McNeely of Bosch GmbH for their collaboration and advice. Additional contributors at Zygo include Senthil Balasubramaniam, David Grigg, Randy Young, and Mike Majlak. Derek Griffith, David Emrie, Jon Everett, and Stephen Fantone of Optikos Corporation performed the optical design for the probe and contributed to the experimental breadboard.

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