

Interferometric measurement of injection nozzles using ultra-small fiber-optical probes

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The measurement of boreholes with diameters smaller than 500 μm is a demanding task that cannot be performed using state-of-the-art production metrology. In this letter, a miniaturized fiber probe with a diameter of 80 μm is presented. A probe is used for low-coherence interferometry to conduct highly precise measurements of form deviations of small boreholes. Measurements conducted in nozzles are also presented. The results prove the potential of the fiber-optical sensor for quality inspection of high-precision parts, such as injection nozzles, for common-rail diesel engines.

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The shape of spray holes in modern fuel injection nozzles for diesel engines is a key factor in minimal pollutant emission and economic fuel combustion. Any deviation from its design shape significantly affects spray breakup, leading to unequally distributed flow and pressure changes^[1].

The measurement of spray holes poses a major challenge towards modern production metrology, because these holes can have diameters of as small as 150 μm , with a tendency towards even smaller diameters in future systems. There are several measuring principles for the inspection of injection nozzles. These can be categorized into tactile^[2] (or with a gauge), opto-tactile^[3], optical^[4], and electrical principles^[5]. Common measurands include diameter and fuel flow. Only a few principles offer the possibility for more than just point-wise probing. A fiber-based approach, which can be used to scan inside small boreholes, has been described in Ref. [4]. Due to many factors, including the small measuring range of ~ 30 μm , complex and expensive heterodyne interferometer set up, and restrictive patent situation, this fiber-based approach has not been as established as the other methods mentioned.

This letter presents an interferometric measurement system based on fiber-optical components, which can be minimized for the inspection of injection nozzle spray holes. Evaluation measurements were conducted with a spark-eroded micro-hole array.

The measuring principle is based on low-coherence interferometry. The key element of the system, which has been developed at Fraunhofer Institute for Production Technology, is the fiber-based sensing probe and fiber-coupled interferometric evaluation unit (Fig. 1). Both elements utilize the interferometric principle: the fiber-based Fizeau interferometer is used as sensing probe and encodes the measurement distance, which is then decoded in the Michelson interferometer. Two superluminescent diodes (SLD) are coupled into the system as a supercontinuum, low-coherence light source with two

shifted wavelengths for additional beat frequency. Single-mode couplers carry the light to the sensing probe, where Fresnel reflection divides the light into a reference and a measuring beam. The optical path difference (OPD) between these beams is compensated in the Michelson interferometer by an appropriate length difference between beam splitter and reference mirror and the tilted mirror, respectively. The characteristic interference pattern is then detected by a charge-coupled device (CCD) line camera and processed by a computer. The distance of the measuring object is correlated with the lateral position of the fringe center on the CCD chip, leading to a pixel value that encodes the distance.

Working distance and measuring range can be adjusted with the angle and distance between the tilted mirror and the beamsplitter cube. The fact that the fiber-based Fizeau interferometer is build up as common-path interferometer is an outstanding system advantage. This is because measurement and reference paths are exposed to the same thermal conditions that minimize thermal drift due to dissimilar fiber-lengths. Furthermore, there are no mechanical elements required, such as linear stages or piezoelectric actuators, for balancing or varying the OPD. The system provides a variable working distance of around 100 μm and a measuring range of approximately 160 μm .

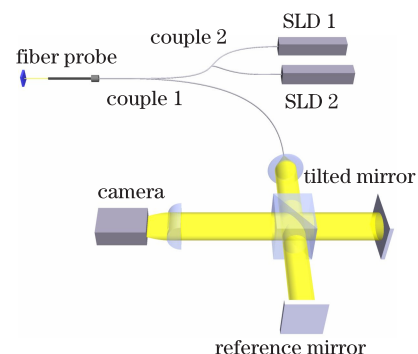


Fig. 1. Setup of the fiber-optical interferometer.

A detailed description of the setup and processing of the interference signal can be found in Ref. [6]. The calibration of the system and estimation of its measurement uncertainty is described in Ref. [7].

With the need for flexible, miniaturized probes with interferometric accuracy, optical fibers provide excellent properties for the realization of highly accurate systems for measurement of rotation-symmetric features, such as injection nozzle spray holes. Fiber-optical probes can be designed with integrated elements, either for beam shaping (i.e., focusing or collimating) or beam deflection. As shown in Fig. 2, this can be achieved without the need for assembly of micro-prisms or lenses. Figure 2(a) shows a bare fiber probe design with a singlemode fiber. Beam deflection can be realized with precision grinding of the fiber end surface using diamond lapping discs and a special bare fiber grinding machine, which provides grinding with defined angles. For a 90° beam deflection, the fiber is ground with an angle of 45°. The measuring beam is then deflected by 90° by total internal reflection (TIR). Furthermore, Fig. 2(a) shows that the measuring beam exits from the fiber tip with a divergent beam shape, resulting in a spot size that grows with increasing working distance.

To overcome large spot sizes for divergent beams from bare singlemode fiber probes, a piece of graded index fiber (GRIN) can be fusion-spliced to the fiber tip (Fig. 2(b)). Cut to the length L , the GRIN-fiber can act as a so-called fiber lens with the focal length given by

$$f(L) = \frac{n \left(1 - \frac{w^4}{w_0^4} \right) \cos(g \cdot L) \sin(g \cdot L)}{g \cdot n_0 \left[\sin^2(g \cdot L) + \frac{w^4}{w_0^4} \cos^2(g \cdot L) \right]}, \quad (1)$$

where w_0 is the waist size of the beam that leaves the singlemode fiber, n is the refraction index of the medium into which light beams emerge from the fiber lens (air or micro-prism), g is the gradient constants, and n_0 relate to the refraction index profile of the used GRIN-fiber. The factor w depends on the wavelength λ

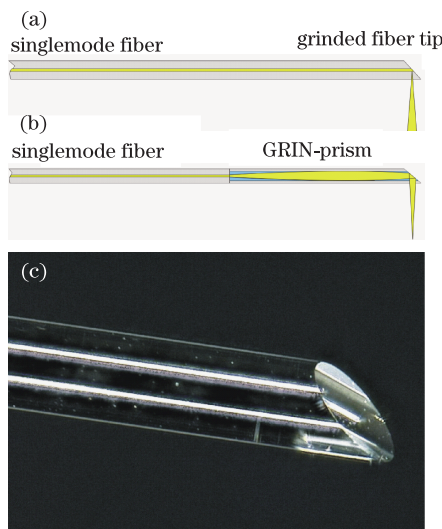


Fig. 2. Fiber-optical probe with grinded tip for 90° beam deflection. (a) Bare singlemode fiber probe, (b) focussing probe with GRIN prism, and (c) 80-μm fiber-optical probe.

by $w = \lambda / (\pi g \cdot n_0)^{[8]}$. The GRIN-fiber can also be ground with an angle of 45°, thus the fiber tip acts as a so-called GRIN-prism with beam shaping.

As proposed in Ref. [9], we designed the probe in all-fiber design using reduced cladding (RC) singlemode fibers. The probe, which was also used for the evaluation measurements, was fabricated with a FiberCore SM800 RC-fiber with a mode Field diameter of 4.2 μm and a cladding diameter of 80 μm. The prototype is shown in Fig. 2(c). The spot size for this prototype was approximately 7 μm.

In order to investigate the measurement of micro-boreholes in the injection nozzles, the presented measurement system was integrated into an industrial form measurement machine (Fig. 3) capable of performing routines to adjust specimen position (decentration and tilt) and automatically execute the measurement motion (Fig. 3). The measurement result feedback in the measurement machine was implemented through an analog interface, which also enabled the usage of the machines metrological analysis software.

The specimen used for the experiments was a small disc with 25 micro-boreholes with a diameter of 125 μm. The boreholes were produced using the same process, process parameters, and materials used in the fabrication of injection nozzle spray holes.

The adjustment of the specimen position was executed with a miniature microscope, which was also used to evaluate the displacement of the micro-borehole center (Fig. 4). The resulting displacement was corrected using the form measurement machines positioning adjustment routines. The measured positioning adjustment uncertainty was about 1 μm.

The roundness of one micro-borehole was measured to evaluate the presented interferometric measurement system. The measurement procedure was realized using a miniature microscope, which was used mainly for positioning fiber-optical probe in the micro-borehole (Fig. 5).



Fig. 3. Industrial form measurement machine with an integrated fiber optical measurement system.

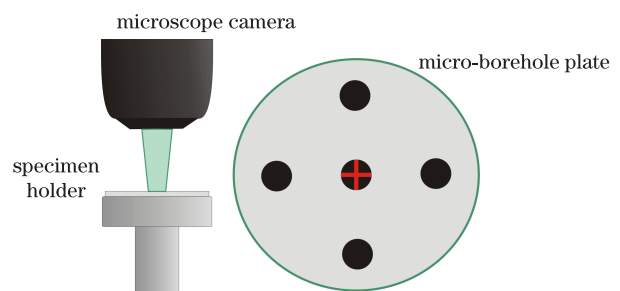


Fig. 4. Positioning adjustment of the borehole center point.

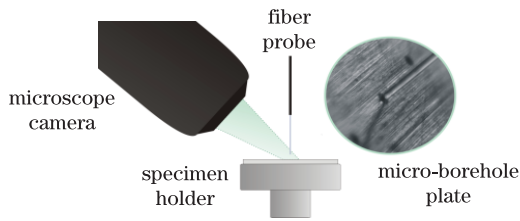


Fig. 5. Positioning of the miniature fiber optical probe and measurement of roundness.

The fiber-optical probe concept selected for the measurements was a singlemode fiber with a diameter of 80 μm . The singlemode fiber had no beam shaping, and its end surface was diamond ground in order to achieve a beam deflection of 90° . The average roughness values, S_a , of the ground fiber optical end surface was under 10 nm, enabling a uniform reference wavefront.

With the aim of reducing any possible fiber vibration to insignificant values during the measurement, a stabilization ferrule consisting of carbon fiber reinforced plastic (CFP) was used. The free fiber length without ferrule was about 15 mm. An angular velocity of 4 degrees per second with a measurement rate of about 1 kHz was used to rotate the specimen in order to measure the borehole roundness.

The resulting interference patterns acquired from the reflection at the borehole surface can be observed at almost the complete perimeter extension, which has an excellent signal-to-noise ratio (SNR) and interference modulation depth. The use of filters in the signal frequency domain and a robust processing of interference patterns allow for the measurement of the roundness profile of a micro-borehole with a diameter of 125 μm (Fig. 6).

The measured roundness values of the injection nozzle spray holes indicate the feasibility of ensuring quality control at micro-boreholes despite its ultra small dimensions (i.e., borehole diameter of 125 μm and probe diameter of 80 μm). Moreover, the measured roundness values indicate realistic outputs, taking into account the very small production tolerances of an injection nozzle (i.e., roundness deviation of 1.7297 μm for global tolerance under 5 μm) (Fig. 7). The standard deviation for five repeated measurements along the same trace is 0.06 μm .

Compared with measurements with an opto-tactile fiber probe, which have been presented in Ref. [3], the fiber-optical interferometer is a promising approach. The measured positioning adjustment uncertainty was about 1 μm , because it provides faster measurements and scanning capability that enable the complete three-dimension-d-assessment of the lateral surface structure of the hole. The repeatability for measurements with the opto-tactile probe is between 0.6 and 1.44 μm for the roundness specification^[3]. Depending on the positioning accuracy of the probe positioning, this repeatability can be smaller than 0.1 μm for the presented interferometric fiber sensor.

We have described a fiber-optical measurement system based on low-coherence interferometry. This is used to measure and analyze the production quality of injection

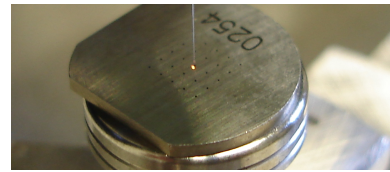


Fig. 6. Roundness measurement procedure of a borehole with diameter of 125 μm .

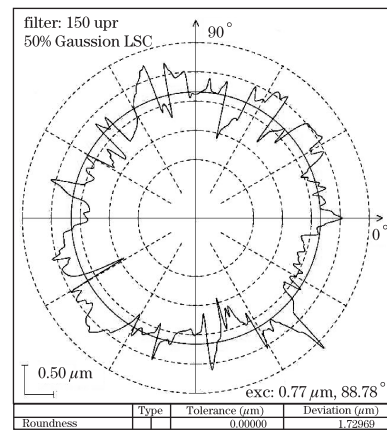


Fig. 7. Roundness measurement protocol of a borehole with diameter of 125 μm and roundness deviation of 1.7297 μm . upr: undulations per revolution; exc: excentric; LSC: least squares circles.

nozzles and micro-boreholes. The high miniaturization of the fiber-optical probes with a diameter of 80 μm has allowed for the measurement of these small boreholes with borehole diameter of about 125 μm .

The obtained interference patterns and measurement results show the robustness of this metrological approach. Thus, this approach can be utilized in further measurement tasks.

Future investigations will be carried out in order to validate the roundness measurement results. An industrial, coordinate measuring machine (CMM)-integrated fiber-optical probe^[10] will be used to measure the borehole and compare the acquired values. Another measurement using a similar fiber-optical sensor will be carried out as well. For an improved probe performance, the design with ground GRIN-fiber tip shall be realized. Further miniaturization of the probe tip can be achieved by tapering the fiber. Fiber tapers with a diameter of 40 μm have already been achieved, although a sensing probe must be used. The effects of the graded index on the beam, which transverses the GRIN-fiber perpendicular to the optical axis after TIR, must also be simulated carefully as a first step. The grinding of the GRIN-fiber has to be studied as well. Finally, beam shaping and interferometric referencing can be improved by grinding an exit window parallel to the fiber axis (0° orientation).

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