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SEMI-AUTOMATED MEASUREMENT OF INJECTION NOZZLES USING FIBER-OPTICAL LOW-COHERENCE INTERFEROMETRY

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Abstract – The roundness measurement of boreholes with diameters less than 500 microns is a challenge that cannot be addressed with conventional metrology such as tactile measurement. This paper presents a setup for semi-automated positioning and roundness measurement of boreholes with diameters down to 160 microns using fiber-optical probes and low-coherence interferometry. The results contribute to sophisticated nozzle design and testing of final parts such as common-rail diesel injection nozzles.

Keywords: roundness measurement, common-rail injection, fiber-optic sensor, micro-boreholes, low-coherence interferometry

1. INTRODUCTION

Micro-holes with diameters less than 1 mm are used in a wide range of technical applications. In most utilizations, a liquid or gaseous medium flows through the micro-channels to fulfil various functions: Combustion engines use injection nozzles to atomize the fuel into the combustor. The geometry of the nozzle spray holes highly affects the fuel combustion process through the spray pattern and thus the fuel consumption and soot production [1]. In aviation technologies, micro-holes are used for boundary layer suction which makes turbulent airflows become laminar. Gas turbine blades are often cooled by means of a channelling system and micro-holes on the surface [2]. In all applications, the exact geometry and form of these holes is crucial to the specific function and performance of the part [3]. However, the use of Electro Discharge Machining (EDM) makes it difficult to keep tight geometrical tolerances.

To assess the geometry of the micro-hole feature without destroying the part, there are only a few present measuring methods, mostly based on modified coordinate measuring machines (CMM) with integrated fibre probes. In [4], the deformation of a non-optical fibre probe is monitored. Once the probe touches an inner surface, the fibre stem is deflected. This deflection can then be added to the machine's coordinate readings. Other groups have introduced vibrating tactile probes where an electrical circuit between two vibrating arms is closed once one arm hits a surface [5, 6]. The duration of this short circuit indicates the probe's distance to the wall. Piezoresistive devices involve cantilevers with lengths up to a few millimetres that cover only a short measurement range [7].

There have been other approaches that involve touching and non-touching cantilevers and styluses. However, most methods provide only very low test frequencies and acquisition of single points which makes the exact measurement of a hole's circumference or even cylinder barrel surfaces extremely time-consuming.

In conclusion, non-destructive measuring methods are required, which can pass through given micro-holes down to 150 µm (and even less) and gather many points in short time. In this paper, a solution for semi-automatic form testing of micro-holes used in injection nozzles is presented. For this purpose a fibre-optical measurement method has been developed, that addresses fast measuring in confined spaces.

2. INTERFEROMETRIC SHORT-COHERENT DISTANCE MEASUREMENT

The measurement system introduced within this paper is based on the low-coherence interferometry in a common-path setup [8]. A narrow-band and thus short-coherent light beam is projected onto the specimen surface by means of a fibre-optical sensor. A fraction of the scattered light re-enters the fibre into a specially designed spectrometer. The Fourier transformed signal supplies the distance *d* shown in the schematic design in Fig. 1.

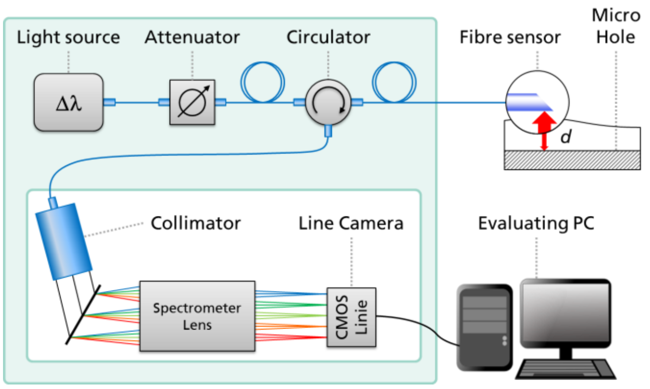

Fig. 1. Schematic of the measurement system consisting of optical setup, fibre-optical sensing probe and evaluation unit.

The measurement system uses a super-luminescence diode (SLD), which continuously sends a near-infrared light beam through a single-mode fibre. A circulator couples the light into the fibre-optic sensor. The sensor tip is polished to an angle of 45° to guide the light laterally outside the fibre. The light is reflected back both at the fibre end, which acts as the interferometer’s reference, and the specimen surface. These two wave packets interfere with each other due to their matching coherence. After passing the spectrometer, the interferogram is projected onto a CMOS line detector and is seen as an amplitude modulation on the SLD’s spectrum (Fig. 2).

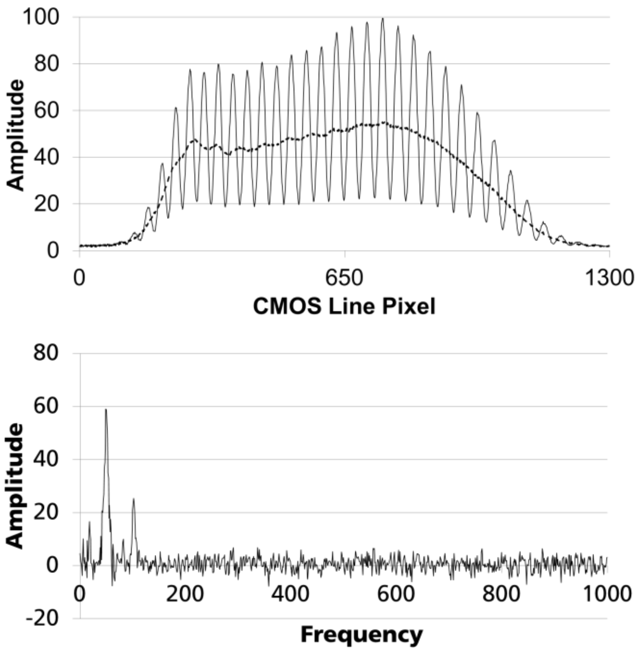

Fig. 2. a) Wavelength spectrum of the SLD light source and added interference modulation by measured surface.
b) Fourier transform of the modulation (second peak due to multiple reflection between fibre tip and surface).

The camera signal is read out by a common personal computer. After passing a couple of specific signal processing filters, the signal is Fourier transformed. The predominant frequency in the frequency domain presents the measured distance *d* (Fig. 1): The higher the frequency, the larger the distance.

Using the single-mode fibre “Corning HI780”, the beam exits the fibre core with an angle of divergence of 1.93°, meaning the simulated RMS spot diameter varies between 6 µm at 200 µm distance and 70 µm at 1 mm distance. The divergence can be partially compensated with focussing graded-index fibre sensors which will not be discussed within this paper’s scope. Additionally to the divergence, the fibre cladding acts as a cylinder lens, thus focusing one axis of the beam. For the reasons above, it is wise to centre the hole to be measured with the machine’s axis of rotation, so that the measured distance varies as little as possible.

To avoid measurement uncertainties and unwanted effects like averaging, the spot is to keep as small as possible throughout the measurement. Tilted surfaces lead to weak signals as the light is reflected away from the fibre. Rough surfaces that scatter the light can diminish this effect.

The system features a maximum measurable distance between fibre end face and specimen surface of 0 to 2 mm, depending on the effects mentioned above. The measured points can be acquired with sampling frequencies up to 140 kHz and an axial repeatability of 200 nm can be achieved thanks to subpixel evaluation.

Two measurement setups are feasible: The rotation of the specimen around the fixed fibre sensor and the rotation of the fibre sensor inside the fixed borehole. The latter variation requires the exact and quite fault-prone calibration of the rotation axis and the fibre tip but technically allows the measurement of diameters and the absolute hole geometry. On the other hand, a fixed sensor is easily realized and allows the fast measurement of roundness along the hole depth, the straightness of the hole walls and the hole’s cone angle using common form testing machines.

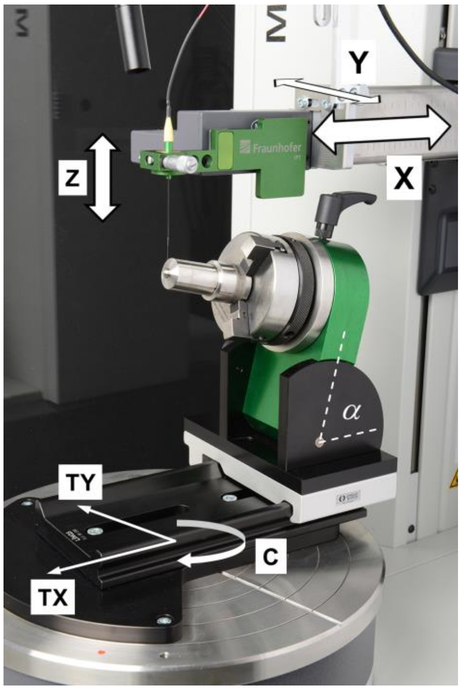

Fig. 3. Machine setup for bore hole measurement.

2.1. Nozzle mount

Completing the measurement setup, a specialized positioning unit for form measurements was developed. Common form measurement machines offer a rotary table as a specimen holder along with typically two linear axes to position the probe or stylus. In this case, a Mahr MarForm MMQ400 was used. The nozzle spray hole to be measured is inclined by an angle α between 45° and 90° in relation to the injection nozzle’s axis. For the right positioning and adjustment of the nozzle, a special mount has been developed. A chuck that holds the nozzle can be tilted by α (0° – 90°) with 1/12° uncertainty using a nonius scale (not seen in figure) and rotated along the nozzle axis which allows the measurement of all spray holes. The mount and parts of the used measurement setup are shown in Fig. 3.

2.2. Hole/sensor positioning

For precise positioning, an image processing system was implemented. A macro camera system attached to the machine's X-axis is used to capture both fibre tip and borehole.

First of all, the spray hole needs to be positioned coaxial to the table's rotation axis: The macro camera system identifies and keeps track of the topmost spray hole, while the table is rotated. Several images in different angular positions are taken. As the table is rotated, the centre point of the spray hole travels on an ellipse (not a circle, due to camera tilt) whose centre again represents the rotation axis. An image processing algorithm processes the images taken and calculates the coordinates of the rotation axis within the camera image. The next step calculates the vector of decentration which indicates the distance by which the rotary table needs to be moved. This vector is decomposed into its components along the table's linear fine adjustment axes TX and TY which are automatically moved to align the spray hole. After the alignment of the hole, the fibre tip is identified and the distance to the hole centroid is calculated. Since the camera system pictures only two dimensions, the fibre tip needs to be moved to the level of the hole opening. The X-axis of the measurement machine is used to automatically position the hole on the imaginary Y-axis in the camera picture. The remaining deflection towards the hole centroid is adjusted manually. Once spray hole and fibre are adjusted, the sensor can be dipped in for measurement (Fig. 4).

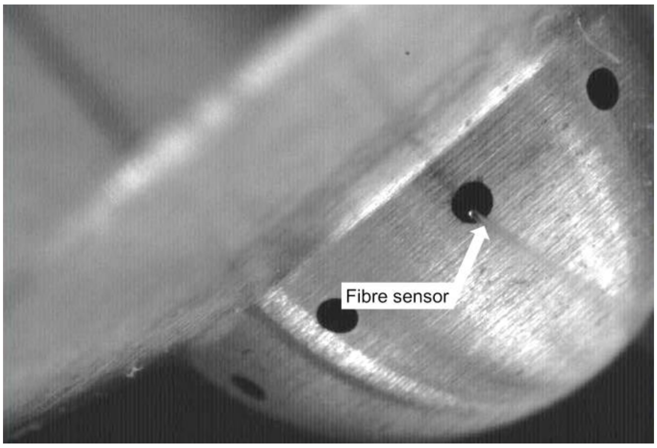

Fig. 4. Camera picture used for automatic positioning of hole and fibre sensor.

2.3. Form testing

Tactile styluses are used with a nominal distance 0 and can be deflected to both sides, reporting both positive and negative values. Before the actual measurement, the probes are zeroed to allow maximum measuring range. Although the fibre-optical system can only measure positive, absolute distances between fibre tip and surface, a fixed distance of typically 300 to 400 µm is used as the nominal working distance. This way, the measurement machine can zero the sensor without touching the surface. Furthermore, in tracking mode, where a surface is scanned whose slope exceeds the measurement range, the machine's axes can be used to maintain the nominal working distance.

Common optical fibres feature smallest diameters of 125 or 80 microns, thus allowing the assembly of sensing probes with such dimensions. Taper technologies can reduce the diameter down to 40 microns. However, tapered fibres have a decreased numerical aperture, due to the reduced fibre core. The borehole diameter should not be smaller than the double fibre diameter to avoid accidental wall contact due to positioning uncertainties. Once the fibre sensor is dipped into the hole, the rotation of the nozzle produces a polar surface profile that can be used to calculate the roundness of the inner surface. The movement of the fibre sensor along the Z-axis produces line profiles that can be used to calculate the straightness of the surface. The data points are acquired without touching the wall, which allows high-speed scanning measurements. The measurement system is fully integrated into the used form testing machine, so that almost every form testing program of the software can be used.

Fig. 5 shows the schematic measurements process where the roundness in four heights and four linear profiles were measured. The holes are conically shaped, therefore, it is crucial to check the minimum distance between fibre and surface over the hole depth.

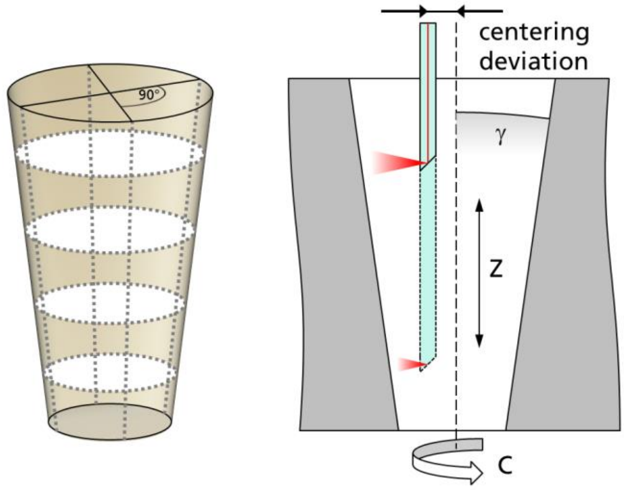

Fig. 5. Schematic measurement process of conical spray hole.

Four straight lines with a relative angular displacement of 90° have been measured with a lateral accuracy of 0.01 µm. Two opposite lines are used to calculate the spray hole's cone angle. Fig. 6 shows the profile of two line pairs, each profile with its correspondent linear regression line. The first measurement (0°, 180°) yields a half cone angle γ of 1.43°. In this orientation, the hole's axis of symmetry differs from being parallel to the Z-axis by $\beta = 1.15°$. At 180°, the radius of the inner opening can be seen. The measurement along the orthogonal section (90°, 270°) yields a half cone angle γ of 1.66° and an axis deflection of $\beta = 1.84°$. As already mentioned, the used measurement mode—rotating the part around the sensor—cannot be used to calculate absolute diameters of the hole since the distance values are relative and may only be interpreted within one profile.

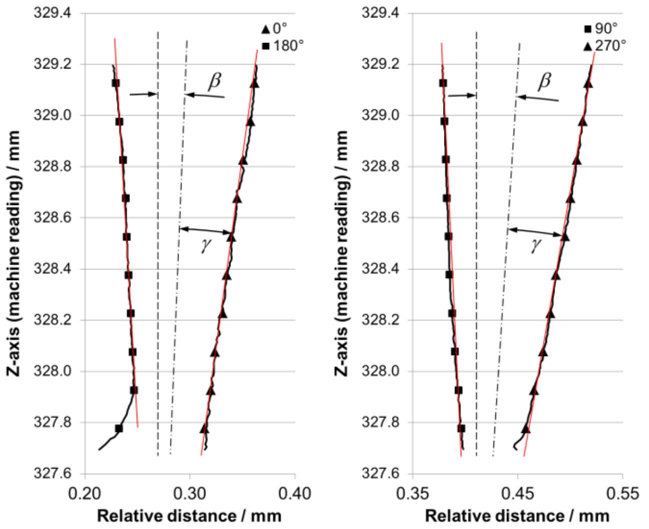

Fig. 6. Line profiles of straight measurements at the angular positions 0°, 90°, 180°, 270° and linear regression lines.

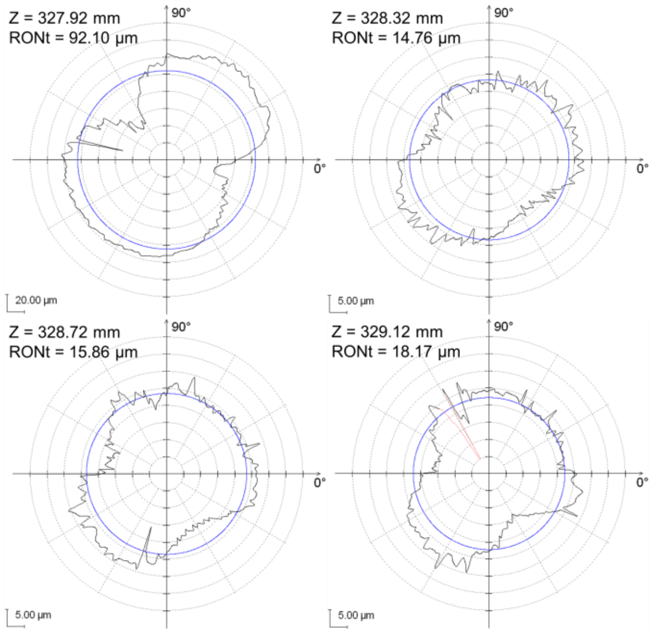

Fig. 7. Polar profiles of roundness measurements at the heights 327.92 mm, 328.32 mm, 328.72 mm and 329.12 mm.

Fig. 7 shows polar profiles that were acquired in four different heights with an angular accuracy of 0.11°. The profiles were filtered with 150 undulations per revolution (UPR) and the Least Square Circle (LSC) fit was used. The roundness error seems to slightly increase towards the outer opening. The high roundness error of 92.10 µm is caused by the edge rounding on the inner hole opening.

4. CONCLUSIONS

A setup for non-destructive micro-hole testing has been presented. A specially developed mount offers exact positioning of the nozzle and thus the spray hole to be measured. The high-speed fibre-optical interferometrical measurement system allows an insight into spray hole form tolerances such as roundness and straightness, which play a crucial part in combustion efficiency and behaviour. Future work concentrates on further sensor miniaturisation and full process automation.

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