Measurement 57 (2014) 25–32

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Integration of fiber-optic sensors in measuring machines

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ARTICLE INFO

Article history:
Received 10 January 2014
Received in revised form 8 July 2014
Accepted 17 July 2014
Available online 31 July 2014

Keywords:
Fiber-optic
Roundness measurement
Nozzle orifice
Non-contact measurement
Form inspection
Image distortion
Image processing

ABSTRACT

In last years, optical metrology due to its capability in miniaturization and sensitivity became the primary solution in measurement of complex geometries and fragile pieces. Here, we propose a promising approach to perform highly accurate distance measurements using low-coherence fiber-optic sensors for quality inspection of nozzle orifices in fuel injection systems. In this effort, we develop an adaptive image processing algorithm in MATLAB and install the necessary hardware on a form tester to accelerate and simplify the aligning process. As a result, the repeatability of measurements is one order of magnitude improved while the standard deviation is almost 60% reduced.

1. Introduction

Recent technological advances in manufacturing enables the fabrication of complicated and small sized workpieces. Tactile probing systems, as traditional means of measurement lack enough resolution and accuracy for inspection of these products. In addition, such techniques could lead to deformation or damage of the surface. In this regard, various optical measuring methods have been developed which are capable of non-destructive surface inspection like confocal microscopy [1], fringe projection [2], and white-light interferometry [3]. The additional difficulty in measuring the in-hole roundness of small boreholes is that most optical and tactile sensors cannot be miniaturized sufficiently [4]. On the other hand, fiber-optic sensors have excellent optical properties and at the same time are suitable for miniaturization. Dunn et al. [5] used a dual-wavelength interferometer system to measure the form and geometry of rough cylinders and conical surfaces in diesel fuel injection components, however the high cost of the machine and restrictions in measurement of blind holes that have small diameters are the main deficiencies of their design.

This paper introduces an automated measurement technique for micron-sized boreholes (~125 µm), particularly the form deviation of micro-orifices for diesel fuel injectors, which is both simple and fast. Typically, micro-orifices have very tight tolerances (±0.5 µm) and their shape (roundness) is a considered as a determining factor in maximal motor efficiency, and minimal pollutant emissions. Any deviation from its original design shape could significantly affect the spray breakup regimes, flow distribution as well as the homogeneity of the mixture [6–8]. A typical diesel engine nozzle is made of high alloy and chrome steel and able to withstand operating pressures as high as 2000 bar, in the same time it has multiple spray holes which are precision drilled. Despite the fact that different measuring principles are available for injector orifices [9–11], most of them are still limited to simple diameter and flow rate measurements. Although,

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http://dx.doi.org/10.1016/j.measurement.2014.07.004
0263-2241/

fiber-optic sensors are interesting choices for inspection of these micro-boreholes, current method of roundness evaluation base on low-coherence interferometry [4] is complicated and time consuming for small pieces since the adjustment is done manually. Therefore, an efficient algorithm should be designed to meet the industry needs and accelerate the computation process. Here, we present a promising approach to perform highly accurate roundness measurements using fiber-optic sensors. Our approach contains: (a) hardware and (b) software solutions. In the first part, a powerful micro-camera and fiber optic probe are integrated on an industrial form measurement machine. The utilized form tester in this experiment has 3 degrees of freedom and the camera is mounted in a way that captures the top surface of the specimen as well as the probe head. By using image processing functions, a simple and efficient algorithm is developed in MATLAB which is capable of edge detection, decentration compensation and finding the proper coordinates required to position the fiber tip inside a desired borehole in order to measure its form deviation. The proposed technique was successful in resolving the shortcomings of traditional methods by reducing the adjustment time to 50 s, improving the repeatability and precision.

2. Experimental setup

2.1. Low-coherence interferometry

The fiber optic system is based on low-coherence interferometry mentioned in [12–14]. It consists of two units, the first one is a Fizeau-interferometer (Fig. 1a, No. 2) and the second one is a Michelson-interferometer (Fig. 1a, No. 3). The fiber-based Fizeau-interferometer is applied as sensing probe and encodes the measurement distance, which is then decoded in the Michelson-interferometer. As light source, the radiation of two low-coherent, super luminescent diodes (SLDs) is coupled into the system (Fig. 1a, No. 1). Single mode couplers carry the light to the sensing probe, where the light is partially divided into a reference and a measuring beam due to Fresnel-reflection at the end of the sensing probe (Fig. 1b). The optical path difference (OPD) between these beams is compensated in

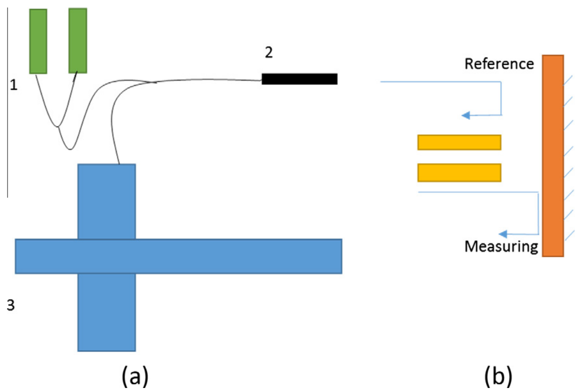

Fig. 1. (a) Set-up of the fiber-optical interferometer 1. SLDs, 2. Common-path interferometer, 3. Michelson interferometer and (b) Fresnel reflection and transmission.

the Michelson-interferometer by an appropriate length difference between beam splitter and reference mirror and the tilted mirror, respectively (Fig. 1a, No. 3). The emerging interference pattern is detected by a CCD-line camera and processed by a computer. Working distance and measurement range depend on the probe design, the adjustments of the angle and the distance between tilted mirror and beam splitter cube. Interestingly, there are no mechanical part required. The system provides a working distance of approximately 100 μm and a measuring range of approximately 160 μm. When placing a test object within the working distance, a characteristic interference pattern arises and is detected by the CCD-camera. The distance of the measuring object correlates with the lateral position of the fringe center on the CCD-chip and leads to a pixel value, which encodes the distance [6,14]. A detailed description of the setup, working principle, calibration and uncertainty is available in [14–17]. For beam deflection, end surface of fiber surface is precision grinded with diamond disks to a predefined angle. A piece of graded index fiber (GRIN) is fusion-spliced to the fiber tip to avoid large spot sizes in diverging beam from single mode fibers [13]. The average roughness value of the grinded fiber optic end surface was under 10 nm, enabling uniform reference wave front. To reduce the fiber vibration during the measurement, a stabilization ferrule of carbon fiber reinforced plastic (CFP) was used. The fiber length without ferrule was of about 15 mm.

2.2. Industrial form measurement machine

The main goal of form testing technology is the metrological acquisition of form deviations on a workpiece by comparing the determined form parameters with the tolerated dimensions to assess the quality of manufactured part. The experiments are performed on a Mahr MMQ-400 form tester. This machine has 3 degrees of freedom and is capable of performing routines to adjust the position of specimen (e.g. decentration and tilt) and execute the measurement motion commands. The result feedback, in the measurement machine was implemented through an analog interface, which enabled also the usage of the machines metrological analysis software. As shown in Fig. 2, the T7W probe is fitted with a motor-driven rotational axis; therefore it is possible to move the probe arm gradually to the required contacting position. As a result, measurements can be performed on cylindrical surfaces, curves and end surfaces. Nevertheless, adjustment and level of probe inside boreholes or on the edges of complex fragile parts could be a time-consuming and hard process. Due to this fact, in this experiment the standard probe arm will be replaced with a customized fiber-optic holder which is responsible for holding the fiber-optic sensor. This would facilitate the transition from traditional tactile metrology to a modern optical technique. Since positioning a 80 μm fiber probe inside ultra-small boreholes could be a challenging task, a light micro-camera is mounted on the system for digital image acquisition. This data is then transferred to a computer and processed using image processing toolbox in MATLAB. The following sections discuss this process in detail.