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MEASUREMENT OF ROUNDNESS AND RUN-OUT WITH DISTRIBUTED FIBER-OPTIC SENSORS

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Abstract − The quality inspection of products poses a challenge towards existing production metrology techniques in terms of accuracy and speed, especially when it comes to inline or in-process measurements. In this terms, optical metrology proves its capabilities, in particular for sensible and fragile work pieces. For the inspection inside small spaces and cavities or for complex geometries, many optical metrology system are to inflexible or cannot be miniaturized enough. Within this work a set-up for a fiber-optic low-coherence interferometer system is described. Due to the high degree of miniaturization of the sensing probe, the system can be used for demanding measuring tasks like roundness of small drilling holes or the run-out of shafts. Different evaluation measurement are presented, which underline the potential of the described system for highly accurate, non-contact inspection of rotational parts.

Keywords: roundness, run-out, fiber-optic metrology

1. INTRODUCTION

The production metrology of today is still dominated by tactile probing systems. Since modern production technologies enable the manufacturing of surfaces and structures, which become more and more miniaturized and fragile, tactile probing is not always feasible. Non-contact optical measurement systems have replaced tactile systems in some areas, like the inspection of MEMS [1] or ultra-precision optics [2].

For the inspection of small boreholes and cavities, most tactile and optical probing systems have the disadvantage, that they cannot be miniaturized sufficiently, although there is a great need for such sensors, which can measure i.e. the inner roundness of injection nozzles.

To ensure a high product quality, not only the inspection of the work piece is essential. The stability and accuracy of the production process itself may also not be neglected. This also includes monitoring of selected machine tool parts i.e. spindles or axes. The commonly used tactile test gauges only offer a low accuracy and cannot be operated in machining process.

The Fraunhofer Institute for Production Technology IPT has developed a highly accurate distance measurement system together with fionec GmbH, Aachen. The system is based on a low-coherence interferometer with a fiber-optic fizeau-probe.

2. SYSTEM SET-UP

2.1. Fiber-optic low-coherence interferometry

As described above, the measurement principle is based on low-coherence interferometry. It mainly consists of two units, whereas both are realized as interferometers, the first one in all-fiber technology (Fig. 1, top) and the second one as a Michelson-Interferometer (Fig. 1, bottom). The fiber-based Fizeau-Interferometer is used as sensing probe and encodes the measurement distance, which is then decoded in the Michelson-Interferometer.

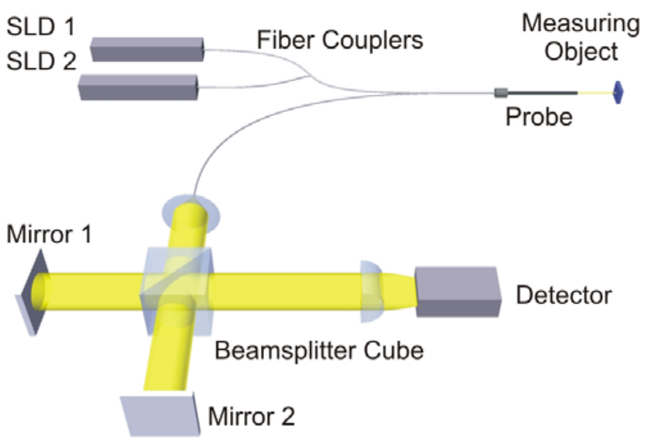

Fig. 1. System set-up for fiber-based low-coherence interferometer

Fig. 1 moreover shows, that only the miniaturized probe has to interact with the measuring object. The receiver unit can consequently be installed at a location further away from the measuring location, if desired. The concept allows, furthermore, the application of distributed probes connected to a single receiver, as demonstrated for the measurement of run-out in sec. 3.2.

The emission of two low-coherent, superluminescent diodes (SLD) is coupled into the system. Singlemode 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. 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 emerging interference pattern is detected by a CCD-line camera and processed by a computer.

The used SLDs feature two different central wavelengths λ_1 and λ_2. The emerging correlogram

$$I(z-z_0)=I_0\{1+g(z-z_0)\cos[2k_0(z-z_0)+\alpha]\} \quad (1)$$

depends on the optical path difference $z\text{-}z_0$, where z_0 is the balanced working distance of the system. Eqn. (1) furthermore depends on the central wave number $k_0=2\pi\lambda_0$ of the light source and the correlogram envelope function $g(z\text{-}z_0)$ and α the phase-shift after reflection from the surface. In case of a light source with a gaussian spectrum, the envelope function takes the form

$$g(z-z_0)=\exp\left\{-2\left[\Delta k\cdot(z-z_0)^2\right]\right\} \quad (2)$$

where $\Delta k=2\pi\Delta\lambda$ denotes the spectral width of the light source [3]. The maximum of the envelope can be used to determine the corresponding point of the object surface. For achieving a higher accuracy, also the phase modulation can be analyzed [4]. The accuracy and stability of the fringe pattern evaluation is influenced by the spectral properties of the light sources. The system described within this work uses SLDs with a full width at half maximum (FWHM) of $\Delta\lambda_1$=21.7 nm and $\Delta\lambda_2$ =25.3 nm. The resulting correlogram shows an additional beat modulation of the envelope, due to the use of light sources with two different wavelengths.

Working distance and measurement range depend, on the one hand, on the probe design (focal length) and, on the other hand, on the adjustments of the angle and the distance between tilted mirror and beamsplitter cube (Fig. 2).

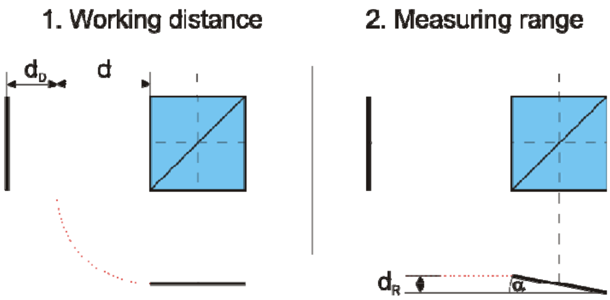

Fig. 2. Adjustment of working distance and measuring range

Compared to other systems, this is an outstanding system advantage, because there are no mechanical elements, such as linear stages or piezoelectric actuators, necessary for balancing or varying the OPD. The system provides a variable working distance of approx. 100-300 µm and a measuring range of approx. 100 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. A detailed description of setup and processing of the interference signal can be found in [4].

2.2. Miniaturized fiber-optic probes

A key feature of the system is the developed sensing Fizeau-probe, which is realized as an all-fiber solution, meaning that beam shaping is also realized by means of fibers. As shown in [5] and [6], collimated or focussed beams can be realized with graded-index (GRIN) fibers. The probe design is shown in Fig. 3a.

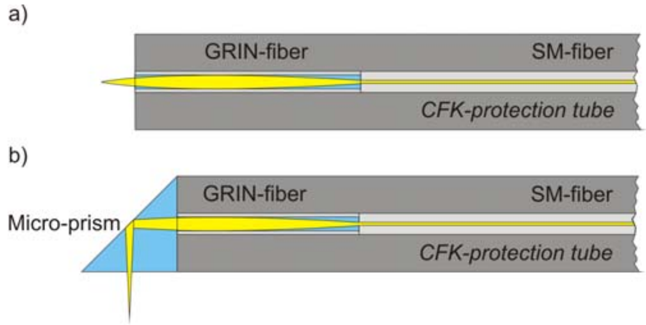

Fig. 3. a) Fizeau-probe design with fusion-spliced GRIN-fiber lens
b) Fizeau-probe design with micro-prism for 90° beam deflection

A singlemode fiber is connected with a piece of GRIN-fiber by fusion-splicing. Cut to the length L, the GRIN-fiber can act as a so-called fiber lens with the focal length

$$f(L)=\frac{n\left(1-\frac{w^4}{w_0^4}\right)\cos(g\cdot L)\sin(g\cdot L)}{g\cdot n_0\left[\sin^2(g\cdot L)+\frac{w^4}{w_0^4}\cos^2(g\cdot L)\right]} \quad (3)$$

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 (e.g. air or micro-prism). The gradient constant g and n_0 are related to the refraction index profile of the used GRIN-fiber. The factor w depends on the wavelength λ by $w=\lambda/(\pi\, g\cdot n_0)$ [6]. To protect the fiber sensor against fracture or other damages, it can be placed into tube made of metal or carbon fiber reinforced plastic (CFP). Especially CFP has proven a high degree of robustness [7].

The probe shown in Fig. 3a can be used for measurements of distances, which are oriented parallel to the probe axis. For in-hole roundness measurements, the measuring beam has to be deflected by 90° by means of an attached micro right-angle prism, like shown in Fig. 3b.

3. APPLICATIONS

3.1. Roundness measurement of small boreholes

The roundness measurement inside small boreholes is a technologically challenging task, because not only the metrological part of the system has to meet high demands concerning accuracy, speed and stability, but also the mechanical setup is complex.

For the inspection of cylindrical objects, the proposed system has been expanded with a high-precision motorized rotation stage with an attached lathe chuck, on which a cylindrical measuring object can be mounted. Fig. 4 shows the setup with an aluminium cylinder with a 1 mm diameter borehole as measuring object. A possible decentering or staggering of the measuring object can be compensated within the mechanical set-up by means of tilt adjustment knobs.

The sensing probe can be lowered into the borehole with an additional linear stage. As shown in Fig. 4, the attached micro-prism deflects the measuring beam, thus, the cylindrical wall of the hole can be measured by rotating the object. The rotation stage is controlled by a motion controller. For the synchronization of rotation and measurement, both the stage and the controller are configured for a position related trigger signal, which can be used with the framegrabber of the CCD-camera. This method ensures a continuous, fast and stable assignment of the measured radial distance values to the angular positions.

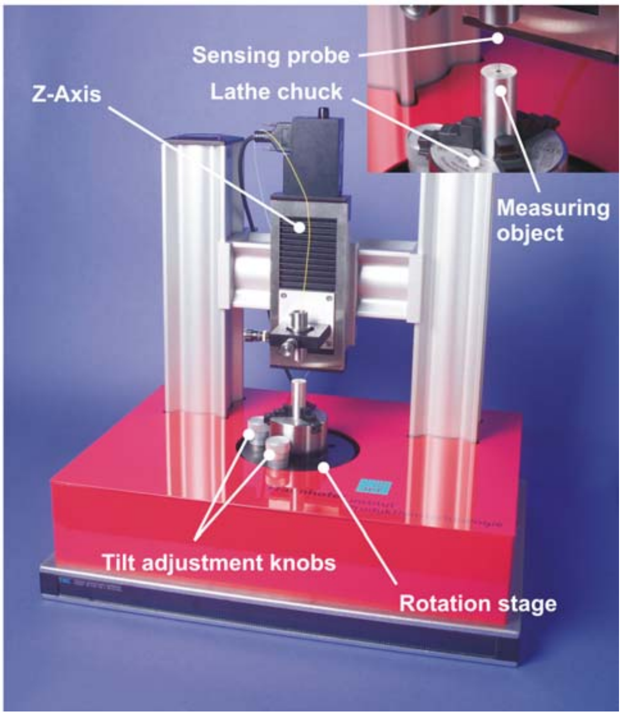

Fig. 4. System set-up for roundness measurements

The angular resolution of the rotation stage is 0.01° with a maximum angular velocity of 80° per second. Since the signal processing of the sensor is capable of a measurement frequency of up to 2 kHz, a single roundness measurement can be finished within 4.5 seconds. The measurement process can be controlled on a personal computer, with a specially developed software, which initiates the motion of the stage and captures the trigger positions and the radial distance values from the sensor. According to ISO 12181 [8] the data are then processed with a Gaussian low-pass filter and the characteristic values *RONp*, *RONv* and *RONt* can be determined, as shown in Fig. 5 for the measurement of a borehole inside a stainless steel cylinder.

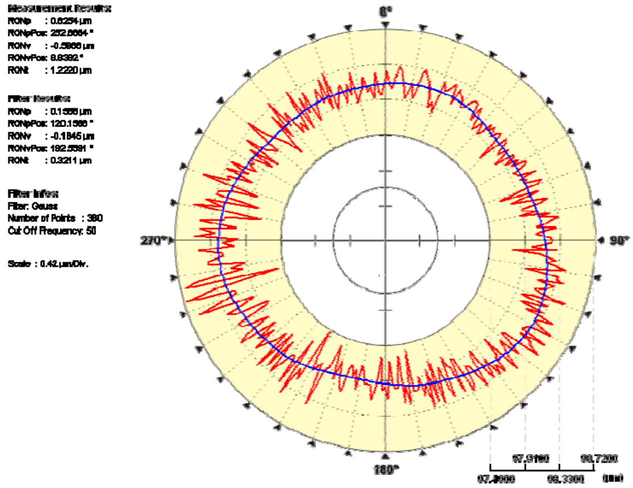

Fig. 5. Polar diagram for the roundness measurement of a 1mm borehole inside a stainless steel cylinder. The total roundness deviation *RONt* was 0,3 µm.

3.2. Run-out measurement with distributed sensors

The real-time monitoring of important machine tool parts, such as spindles and axes, concerning its run-out, is a complex task. In most cases, only small installation space is provided and many conventional measurement systems do not feature the necessary accuracy. On the other hand, monitoring is essential especially for ultra-precision production technologies, where surface qualities with roughness values within the nanometre scale, as well as special functional structures (e.g. for tribology) also within the nanometre scale can be manufactured.

As a solution, the fiber-optic measurement system, which has been described in sec. 2, can be adopted for the cases as mentioned to provide a non-contact measurement with no wear in the part. For the run-out assessment we present a stand-alone measurement set-up, which demonstrates the application of fiber-optic probes for inline monitoring.

Fig. 6 shows the set-up with a spindle, which is being measured by three distributed probes. To rotate the spindle and simulate a continuous machine motion, a low power dc-motor is used. In order to record the current spindle angle and reconstruct the measured perimeter, an encoder triggers the signal processing units CCD-line camera through a frame grabber every time one of its divisions is crossed. The acquired interference patterns are analysed in a computer, which calculates the distances.

The chosen encoder generates a trigger with 3600 TTL-pulses per revolution, ensuring the system an angle precision of 0.1 degrees.

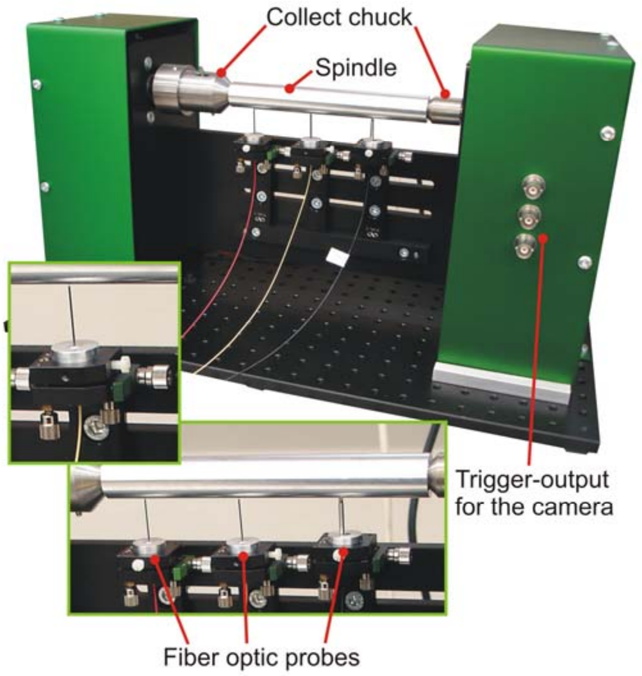

Fig. 5. Set-up of the run-out measurement system

The system moreover makes use of a fiber-switch to receive the signal of distributed sensors, and allows herewith the run-out analysis according to ISO 1101 [9].

In order to control, analyse and show its results, a measurement device specific software has been developed. This application features the same algorithms for the roundness evaluation as the system explained in sec. 3.1 and a run-out evaluation algorithm. The switching procedure is controlled by this application and is synchronized with the data analysis.

The maximum adjustable motor angular velocity is 150° per second (25 r.p.m.), which allows the system to perform a run-out measurement within 7.3 seconds, (assuming a switching time of 2 ms and considering that every probe captures the entire perimeter of the test piece).

The run-out deviation is evaluated by calculating a reference axis (Fig. 6 (c)), which is generated using both reference circles (Fig. 6 (A) and (B)). After that, a tolerance band is created (Fig. 6 (t)) [9].

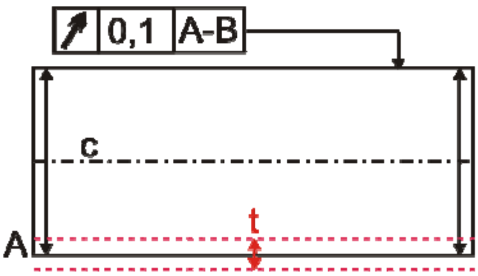

Fig. 6. Run-out definition of ISO 1101: reference circle (A and B), reference axis (c) and tolerance range (t)

In the proposed run-out set-up the measured center distance d_b is compared with a tolerance generated using the circles (ß) (least square circle calculated using d_a) and (µ) (least square circle calculated using d_a) (Fig. 7).

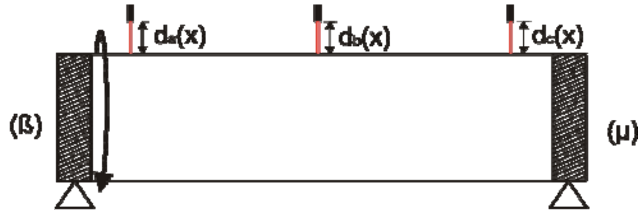

Fig. 7. Scheme of the spindle measurement: Measured distance of the sensor a (d_a), sensor b (d_b), sensor c (d_c), reference circle of left side (ß) and right side (µ)

An example of a measurement result is shown in Fig. 8.

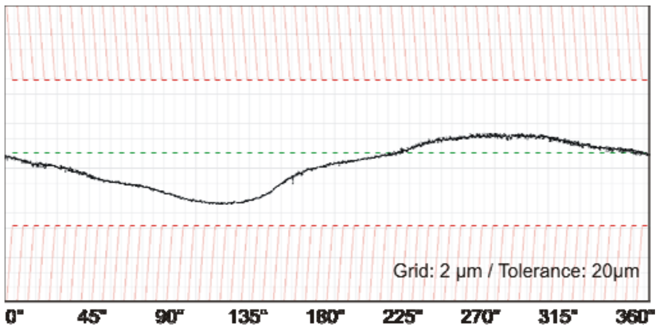

Fig. 8. Measurement result of a run-out taken from the developed analysis software

For the real-time monitoring of machine parts the run-out, as well as the roundness characteristic values can be used. The progress of those variables shows, for example, if the part has a growing wear or if its structured surface is still within the tolerances (detected mainly through the roundness evaluation), as well as vibration or a bending due to a heavy work peace (detected mainly through the run-out evaluation).

In consequence of the use of relative evaluation of the geometrical characteristic variables (comparison between a reference condition and the current measurement) the machine parts can be compared to different initial conditions and record a related condition of the part.

Another advantage of this approach is that the monitoring process bases its evaluation upon analysed characteristic values and not just upon simple measurements, improving the focus of the inspection.

The improvement of the analysis algorithm using a spectrum evaluation of the measured values is planned. This expansion will add more information to the machine monitoring and permit a reliable separation of the repeatable and non-repeatable run-out [10].

4. CONCLUSIONS

Within this work, a fiber-optic measurement system has been described, which has been shown in two applications for roundness and run-out measurement. Due to the miniaturized, non-contact fiber-optic probe, the system is capable of measurements in small spaces, holes and cavities. Multiplexing of several distributed probes with one signal processing unit offers the realization of cost-effective multi-point set-ups for the measurement of complex parts, e.g. camshafts. The high measurement frequency and the robust set-up enables the system for inline- and in-process measurements.

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