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Fiber-Coupled Microoptcal Interferometric Sensor for Precision Engineering Applications

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Abstract:

Industrial inspection of precision manufactured mechanical or optical components requires flexible, accurate, fast and reasonably priced optical sensors. We present a combination of interferometric and confocal sensor based on a fiber-coupled micro-optical probe. Owing to its micro-optical realization, its low mass, and the high data rate the probe head of the sensor can be used for very fast surface contour tracking.

1. Introduction

Recent progress in development and manufacturing of demanding geometrical features confront production metrology with challenges, which cannot be met by existing instruments. This is especially true for optical surfaces, such as aspherical lenses or free form surfaces, but also for components in precision engineering, automotive industries, semiconductor or micro technologies. Optical techniques being developed for this task can be categorized in pointwise scanning and image based methods. Here, we introduce a pointwise measuring sensor, which obtains distance changes, while it scans the contour of a measuring object. This strategy is closely related to tactile sampling. Hence, it provides maximum flexibility but it avoids the drawbacks of tactile instruments.

2. Sensor Arrangement

The microoptical probe head as shown in Fig. 1 works similar to a Fizeau interferometer. The probe is mounted on a bending beam which is driven by a piezoelectrical actuator modulating the optical path length by periodically changing the distance between the probe head and the measuring object. This leads to a characteristic time dependent interference signal [1, 2].

The probe head first collimates the divergent light coming from the end face of a single mode fiber. The measurement rays are then focused onto the measuring object via a GRIN lens or a GRIN fiber while a part of the incident light is reflected back from a reference surface located inside the micro-optical probe. A part of the light reflected from the measuring object couples into the fiber again, propagates towards a photo diode, and interferes with the reference wave. Both, a laser diode as a light source and a photo diode as a receiver are connected to the micro-optical probe via a fiber coupler.

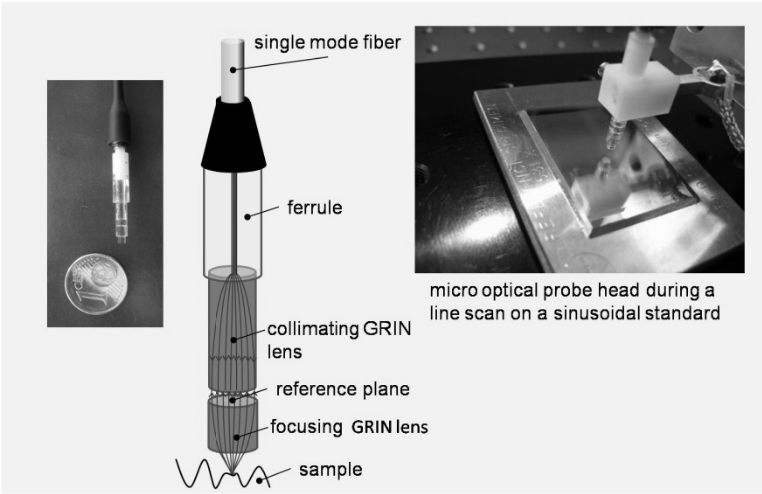

Fig. 1: Scheme of the probe head and photograph of the sensor.

Since the optical path length of the reference wave remains constant, while the optical path length of the measurement arm is periodically modulated, alternating constructive and destructive interference occurs at the fiber output connected to the receiver. The photo diode transfers the optical output irradiance into an electrical signal, which is appropriately filtered, amplified and finally digitally analyzed (see Fig. 2).

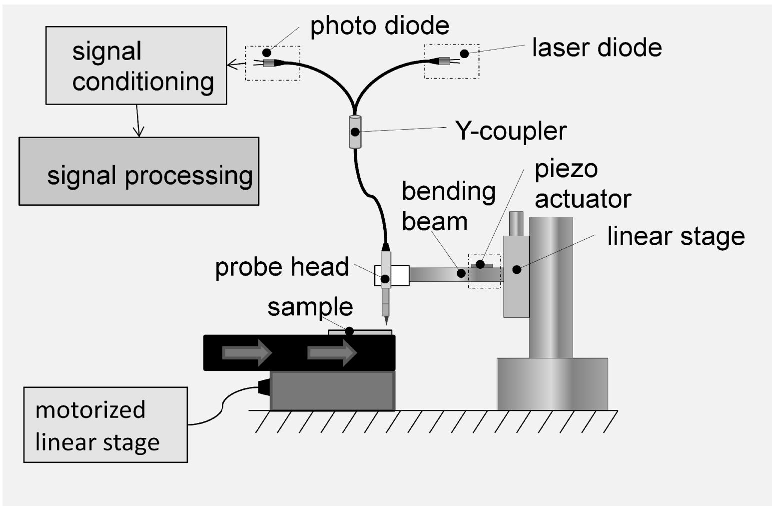

Fig. 2: Schematic of the sensor-setup. During measurement a linear stage moves the measuring object laterally while the sensor head oscillates vertically.

3. Sensor Realization

Photographs of the different types of optical probes developed up to now are shown in Fig. 3. For the bending beam driven by a piezoelectric actuator an inexpensive consumer component is used. The fiber optical arrangement of the sensor enables a flexible handling of the probe head and rather large distances between optical probe head and all other components. The sensor system can be easily equipped with individual optical probe heads, which may be optimized for a specific measuring task. The probe head can be exchanged by a few simple steps.

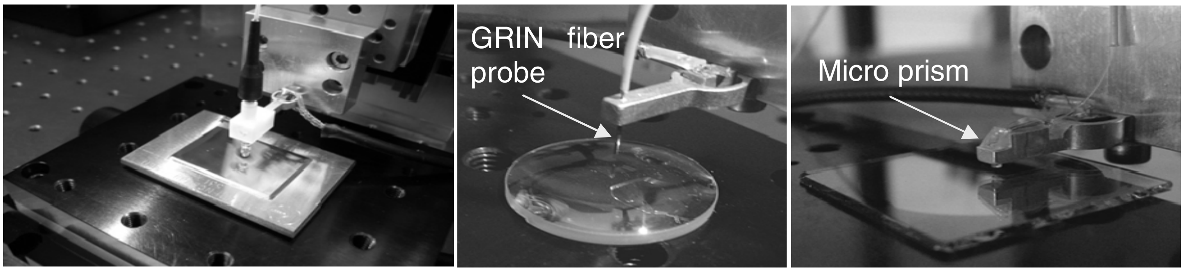

Fig. 3: From left to right: (a) optical probe based on GRIN lenses, (b) optical probe based on a GRIN fiber, (c) prototype of a hybrid probe, where the bending beam acts as a micro-optical bench.

Fig. 3a shows a type of probe head which uses GRIN lenses. First, a GRIN lens of low numerical aperture (NA) collimates the light. In a second step the light is focused onto the object under investigation by a second GRIN lens with a high NA. This allows to measure rather steep flanks [1] as it is confirmed by the measuring results. Unfortunately, this type of probe head is accompanied by a rather high mass, finally leading to a lower resonance frequency of the system of probe head and bending beam of typically 800 Hz.

For the micro-optical probe head also GRIN fibers can be used. Fig. 3b shows a GRIN fiber probe manufactured by Fionec GmbH. GRIN fiber probe heads are characterized by low mass and, thus high resonance frequencies of more than 10 kHz can be achieved. However, the numerical aperture of this version as well as its working distance is rather limited. Except for the probe head the sensor system is built with standard optical components and is therefore of low cost.

A special hybrid probe head is shown in Fig. 3c. In this type of probe the piezo-driven bending beam is simultaneously used as a micro-optical bench, holding a first GRIN lens, which collimates the divergent ray bundle emitted by the fiber end face. Furthermore, a 45° micro-prism directs the light vertically onto the measuring object after focussing through a second GRIN lens. This concept shows several advantages: it combines a high NA of the focussing lens with a rather long working distance. In addition, owing to the reduced moment of inertia this solution provides a high resonance frequency of 4 kHz. This probe paves the way to further miniaturization.

4. Measurement Results

The oscillation movement of the probe head can be well approximated by a sinusoidal function. Consequently, the time dependent interference signal shows a sinusoidal phase modulation, i.e. it differs from a pure sinusoidal function especially in the vicinity of the turning points. This can be seen in Fig. 4 a), where both, the triangular signal driving the actuator and the measured interference signal are plotted. However, if only the linear flanks of the sinusoidal movement are used to analyze the corresponding height position, the measured interference signal itself can be treated as a harmonic sinusoidal signal. Thus, changing the distance between probe and object leads to a phase shift of the measured interference signal. A distance change of $\lambda/2$ results in a phase shift of 2π. In order to extend the range of unambiguity a second laser diode emitting at a different wavelength can be used. Furthermore, if the mechanical system consisting of the bending beam and the optical probe head is driven at its resonance frequency the oscillation amplitude increases significantly and the probe head scans through its focus. Since single mode fibers are used, the fiber end face connected to the probe head acts as a confocal pinhole. This pinhole is imaged onto the measuring object while the oscillation movement of the probe head performs a focus scan. Consequently, confocal peaks occur in the measured intensity signal as can be seen in Fig. 4 b).

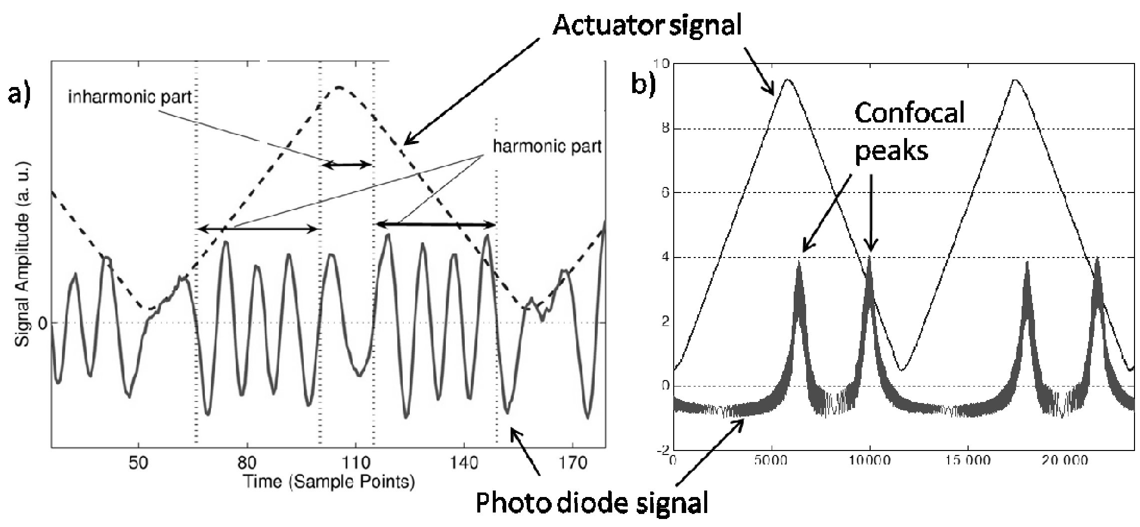

Fig. 4: Measured signals a) driving the bending beam at high frequency resulting in a moderate oscillation amplitude and b) driving the bending beam at resonance frequency (high oscillation amplitude).

Signal Analysis based on Phase Evaluation

The signal's phase can be obtained with a high accuracy in the frequency domain by use of the discrete Fourier transform. For proper triggering we use the triangular voltage signal driving the piezoelectric actuator. Using this technique distance changes on specular surfaces can be measured with a standard deviation below one nanometer [1]. In order to show that the system even works on micro-structured surfaces the measuring object was moved laterally via a precision linear stage (see Fig. 2). For the sinusoidal precision reference specimen 531 by Rubert Ltd. with a period (Sm) of 100 µm and a peak-to-valley amplitude (PV) of 1 µm the profile shown in Fig. 5 results. For this measurement an optical probe head with a NA of 0.3 assembled by GRIN lenses was used.

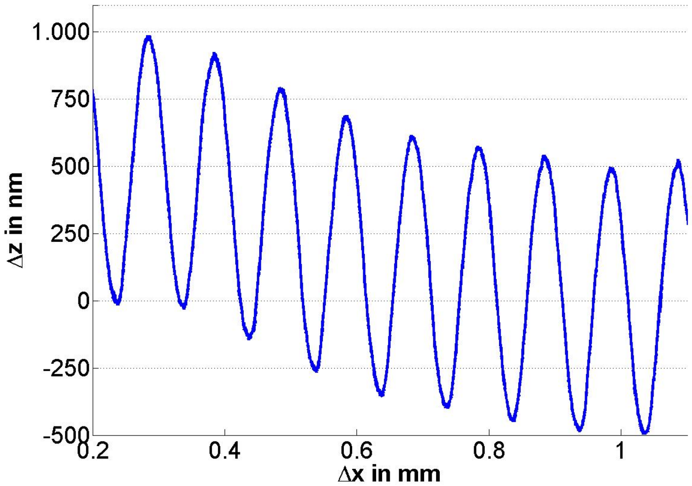

Fig. 5: Measured sinusoidal profile with 100 µm period and 1 µm PV amplitude. (The straightness deviation of the lateral scan axis causes the low-frequency disturbance.)

The advantage of this measurement based on phase analysis is the high accuracy. On the other hand the data rate is limited by the oscillation frequency of the bending beam, e.g. 1 kHz for the measured profile according to Fig. 5. In this case a scanning speed of 0.1 mm/s along the sinusoidal profile was chosen, so that a sampling interval of 100 nm along the *x* axis results. Faster scanning speed requires an increased sampling interval. On the other hand, as mentioned above miniaturization allows increasing the resonance frequency and therefore the data rate of the sensor.

Signal Analysis based on Hilbert Transform

If the so-called analytic signal is generated and analyzed the limited data rate of phase analysis in the frequency domain can be overcome. The real part of the analytic signal is the measured intensity signal, where the oscillating movement of the bending beam causes a

periodic phase modulation. In addition, the analytic signal contains a 90° phase shifted component as an imaginary part. This signal is numerically calculated by use of a Hilbert transform filter [3]. The analytic signal allows us to determine a phase value for each sample point. The sign of the phase change can be derived from the triangular signal which drives the piezoelectric actuator and leads to the deflection of the bending beam. Assuming that the maximum height difference between two consecutive height values is less than $\pm\lambda/4$, possible phase jumps can be corrected by addition of ±2π. Finally, the relation $z(t) = \frac{\lambda}{4\pi}\varphi(t)$ results in height values corresponding to each of the phase values.
The time-dependent distance change leads to a sinusoidal modulation of the optical path length in the measuring arm of the interferometer. Once the sensor is calibrated at a constant distance between optical probe and measuring object, any further distance change can be obtained from the difference between a measured phase response and the phase response represented by the calibrated data set. As mentioned above the crucial point in this context is the high data rate of the sensor which can be achieved. The data rate agrees with the conversion frequency of the AD-converter, which is used to digitize the photo diode signal. Hence, the data rate can be tens or hundreds of MHz which enables very high measuring speed. The amplitude of the oscillating bending beam is several micrometers, so that the interference signal always comprises a couple of cycles.
Fig. 6 shows a measured profile of a convex lens. In this measurement the conversion rate of the used AD-converter was 96 kHz. The height range shown in the diagram covers 130 µm, which is much more than the Rayleigh length of the optical probe. Furthermore, the measuring object was slightly tilted. This results in a little asymmetry of the plotted profile. Nevertheless, the experimental result shows that even for a reflectivity of only 4 % the contour of the measuring object can be obtained with high accuracy and scanning speed.

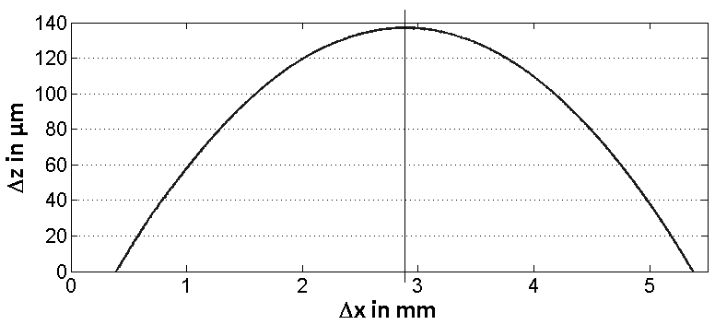

Fig. 6: Measured profile of a convex lens obtained by use of the Hilbert transform method.

5. Conclusion and Outlook

The type of sensor introduced here is still in an early stage of development, so that the complete range of application is hard to estimate at the moment. However, nanometer resolution could be achieved [1, 2] and the applicability of the sensor to measure shape and contour deviations could be approved.

Future work first deals with the improvement of the sensor. The combination of bending beam and optical probe needs to be miniaturized, the signal processing algorithms will be further improved, and implemented in a real time signal processor. In addition, the interferometer will be extended so that dual-wavelength interferometric measurement as well as a combined interferometric and confocal measurement can be performed.

Finally, the sensor shall be combined with appropriate scanning axes, so that its suitability for practical operation can be tested. Owing to its high measuring speed and the robust measurement capability an integration of the sensor into a production machine seems to be realistic.

6. Acknowledgement

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[3] S. D. Stearns, D. R. Hush, “Digital Signal Analysis“, Oldenbourg, 1999