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A NEW APPROACH TO IN-SITU FORMTEST-INTERFEROMETRY

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Abstract – Interferometry is a common method for testing the form of ultra-precise components. However interferometrical measurements are very sensitive to external influences. Due to this reason, in-situ measurements are very difficult to perform, especially in the vicinity of production processes. In this paper we present a new concept for the integration of interferometers in a machine tool and first results of the analysis of fundamental influences on interferometers operated in-situ.

Keywords: interferometry, in-situ measurement, simulation

1. INTRODUCTION

Today in optical manufacturing the surfaces of ultra-precise components are not tested in machine tools. Quality inspection is carried out after the process of fabrication. Routinely, deviations of the form are measured in the optical shop by use of commercial phase-shifting interferometers (PSI). Height deviations are measured by determining the optical phase difference obtained from phase-shifted interferograms [1]. Reworking or local corrections for optimization of the products is difficult, because they have to be reassembled onto the machine. Thereby the precise reconstruction of the measured flaws with respect to the machine coordinate system is very difficult. A possible way to solve that problem is to perform in-situ measurements.

In-situ measurements of surface characteristics during grinding and polishing could deliver very helpful information of the process flow and assist in process control. By this, process parameters can be adjusted directly in the manufacturing step. An additional disassembly for quality inspection is not necessary. Another important aspect is the duration of fabrication and therefore increasing of the output. To minimize the time of process fast measurement techniques have to be used. One promising method is interferometrical formtesting with its possibility of measuring large surfaces in one step.

Normally interferometrical measurements are performed under laboratory conditions to avoid any external influences, e.g. vibrations can lead to an uncertainty in the relative phase difference resulting in measurement errors. An overview of several interferometrical methods, error sources and measuring limitations is given in [2],[3]. Because of their sensitivity interferometers are constructed of massive machined parts and are placed on a granite slab or an air table. Auxiliary equipment, such as motors and cooling fans, are removed or kept at a distance.

Till now integration of interferometrical methods near by or in a machine tool was only possible for the position measurement of the machine axis. But up to now it has not been possible to overcome general problems of interferometrical in-situ formtesting methods.

A measuring instrument functioning in a workshop environment should be immune to machine vibrations, noise, and turbulence which are unavoidable in a machine environment. For that the influence of environmental effects on the contour map of an integrated interferometer has to be studied. The results will serve as initial values for a superior integration concept.

2. CONCEPT

Our proposed concept is shown in Fig. 1 which is mainly based on three components. The first two components include interferometrical measurements with a real instrument whereas the third component deals with simulations that would give an insight into the main influences during in-situ measurements.

Starting at the left side of the figure, we have a specimen with known properties as well as data of the environmental conditions of the work shop and the machine tool. The specimen is tested in the optical shop under laboratory conditions and the results serve as a reference for the following steps.

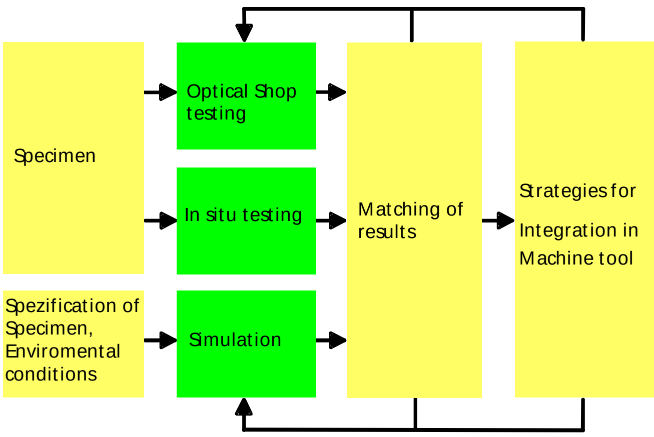

Fig. 1. Concept for the integration of interferometers in a machine tool

The same specimen is assembled on a machine tool and measured by an integrated interferometer. By comparing the measurement results under laboratory and machine conditions, the differences will be analyzed and the results are matched and assigned to external influences. In that context the use of simulation tools is necessary, because simulation can give an insight into the error influences and their effects on a specific measurement.

Recently a simulation tool, the "Virtual Interferometer" has been developed at the Fraunhofer IPT, which allows a realistic reproduction of any physical interferometer in a computer and enables simulation of interferometrical measurements under accurately specified and, thus, perfectly known conditions, helping to provide very detailed information on the measurement uncertainty [4].

The Virtual Interferometer uses non-sequential ray-tracing for the calculation of optical path differences and interferograms, whereby the ray propagation is analyzed until the energy of a ray falls below a given threshold or until a given distance is exceeded. In non-sequential ray-tracing the rays reflect, refract or pass through given optical components according to actual propagation independent of the order in which the components are listed. Hence, non-sequential ray tracing allows simulation not only of optical systems in which rays undergo multiple reflections, like in Fabry-Perot interferometry, but also of effects that are caused by internal reflections or unwanted back reflections from non ideal anti-reflective coatings.

All optical components used in the Virtual Interferometer are 3D solid models that can be described by different types of surfaces and may be placed and orientated freely in a global coordinate system. The optical components may be combined to model virtually physical interferometers. Fig. 2 shows the computer model of a standard Fizeau-Interferometer for testing flats visualized with the Virtual Interferometer.

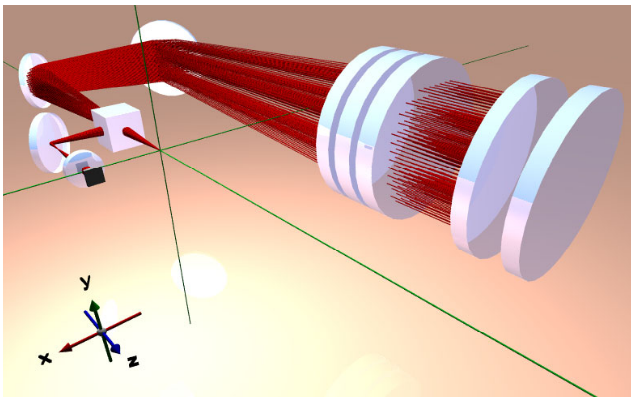

Fig. 2. Simulation of a Fizeau-interferometer

3. EXPERIMENTAL SETUP

A series of experiments were conducted in which an interferometer was mounted onto a machine tool. Using this setup, the form of an apparently plane surface was measured after the completion of a machining procedure. Since the machining of the work-piece was carried out with the interferometer in location, this simulates the conditions within which an in-situ measurement system would have to function. This set of experiments was conducted with the following goals in mind:

a) To gain an insight into the practical aspects of physically integrating an interferometric measurement system into a machine tool.
b) To study the effects of a machine tool environment on the accuracy and repeatability of formtesting using an interferometer.
c) To use the results obtained as a base for future concepts and as a guideline for the research direction to be followed.

We will present the observations and results of these experiments as a first step towards the goal of quantifying the various factors that have made ultra-precise in-situ measurement a challenging task.

3.1. In-situ testing

The Pneumo Precision Comp, a high precision CNC turning centre with a documented motion resolution of 10nm, and repeatability of 50nm was selected as the target machine. A commercially available phase shifting Twyman-Green Interferometer (Fisba µPhase DCI-2 HR) coupled with a 50mm diameter plane objective was mounted onto the movable table of the machine, the same table on which the cutting tool is mounted (Fig. 3)

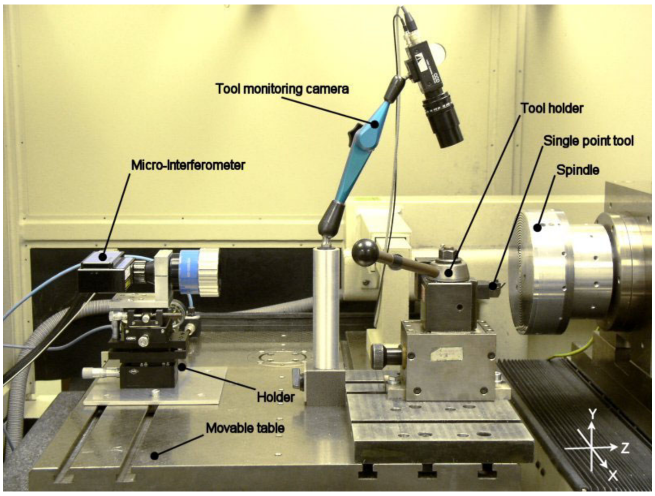

Fig. 3. Experimental setup

In order to provide the interferometer with the capability of being aligned, a holder (Fig. 4) built-up using off-the-shelf motion stages was employed. The holder was capable of 4 degrees of freedom, namely

a) Lift (y-axis)
b) Horizontal slide (x-axis)
c) Tilt (yz-plane)
d) Rotation (xz-plane)

In addition, the machine table was capable of motion along the x-axis, and the spindle was capable of traversing along the z-axis. This lead to a complete flexibility over the alignment of the system.

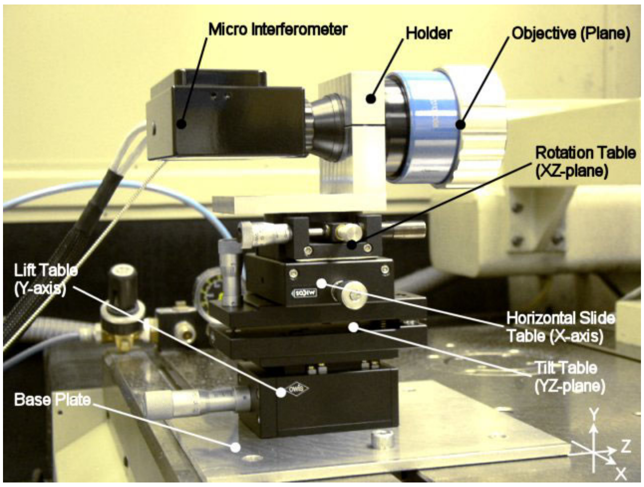

Fig. 4. Holder for the integrated interferometer

The machine and hence, the experiment was located in a climate controlled machine room environment optimized for high-precision manufacturing. The presence of an air-conditioning system in the vicinity induced a fair amount of noise and mechanical vibrations, but no special care was taken to reduce or isolate sources of mechanical and acoustic vibrations.

The work-piece utilized as the measurement surface was an aluminium cylinder (50 mm dia., 20mm height). Three pieces of the same material and dimensions were used over the course of the experiment.

A single point diamond tool was utilized for the purpose of machining the work-pieces. The work-pieces were loaded onto the spindle by means of a vacuum chuck and a centring stud. On the other side a center marker was added which assisted the fabrication process. With that marker it was not necessary to find the center of the work-piece.

3.2. Optical shop testing

In order to validate and compare the measurements carried out on the machine with a reliable reference measurement of the same surfaces, a control setup was developed. For this purpose, the interferometer setup used on the machine was later re-assembled in a standard optical laboratory environment. Care was taken to ensure that this re-assembly procedure caused no changes in the system configuration. Using this setup, the surfaces were measured again, and the results obtained were used as a set of reference measurements.

4. FIRST RESULTS

The series of experiments carried out give an insight into the effect of auxiliary equipment of the fabrication process on the accuracy of interferometric measurement. They mainly dealt with the effect of the workshop environment and residual coolant.

For the analysis a measurement mask had to be applied, because of the infuence of the center marker in the middle of the work-pieces. This was prompted by the high variations in peak-valley values observed in some contour maps. In addition the outer region was also masked to avoid any influences from the aperture of the measurement objective.

4.1. Effect of the workshop environment

As mentioned in the description of the experimental setup, no special care was taken to isolate the interferometer setup from acoustic and mechanical vibrations. The consequence of this was seen during the entire series of experiments, as instability in the interferograms.

It is a well known fact that instability in an interferogram leads to inaccuracies in phase shifting interferometry due to the random phase shifts that are superimposed on the known phase shifts.

In order to gain an insight into the magnitude of inaccuracy injected into the system due to this instability, a series of measurements were carried out on the machine. The results of these measurements were compared with a set of reference measurements obtained from a similar series carried out in the laboratory.

The measurement series comprised of taking five sets of measurements per work-piece. Between each of the five measurement sets, the work-piece was rotated by 90° about it's axis. Each measurement was saved with the tilt removed using the Fisba interferometer software. Measurements in the laboratory were carried out in a similar manner.

The figures below are a sample of the results obtained, and correspond to the in-situ (Fig. 5) and laboratory (Fig. 6) measurements of one of the work-pieces employed. As it can be seen the peak-valley value is lower in the laboratory than on the machine.

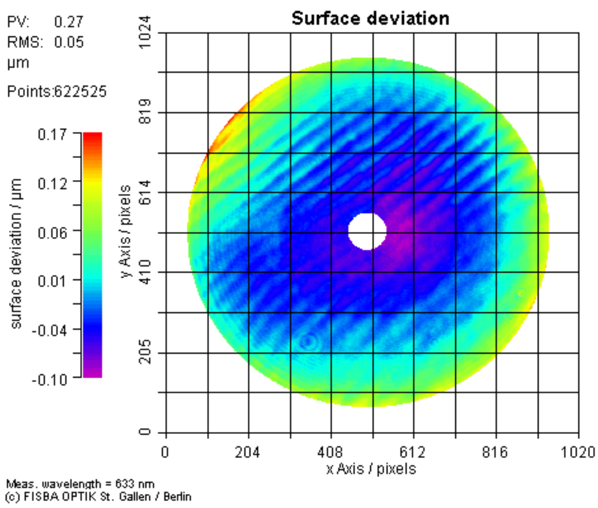

Fig. 5. Contour plot of an in-situ measurement

This increase in the peak-valley value can be attributed to the effects of the machine room environment on the interferometer setup.

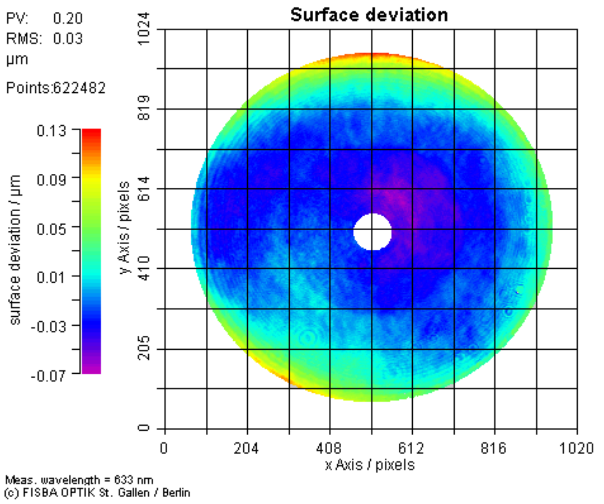

Fig. 6. Contour plot of a laboratory measurement

4.2. Effect of residual coolant

A study of the degree of distortion and the corresponding reduction in accuracy of measurements due to the presence of residual coolant on the surface was carried out. This was done by measuring the surface immediately after a machining pass, without cleaning the coolant off the surface. A second measurement was done after cleaning the surface with ethanol.

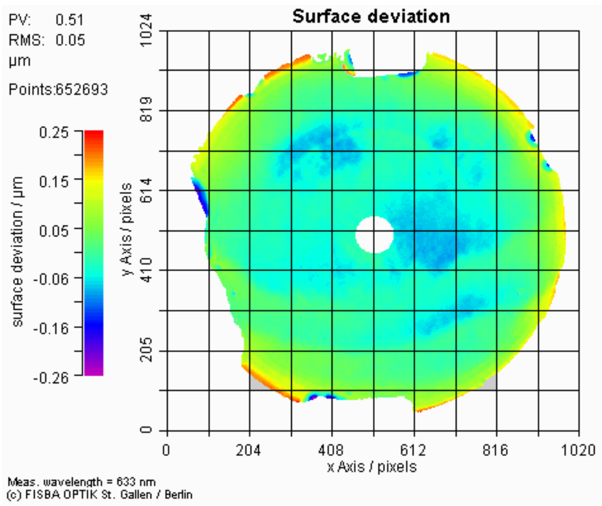

Fig. 7. Contour plot of an un-cleaned surface

Comparing the contour plots of the un-cleaned (Fig. 7) and cleaned (Fig. 8) surfaces, it can be seen that the presence of coolant fluid on the surface forced parts of the interferogram to be excluded from the phase unwrapping process. This resulted in an erroneous contour plot, and inaccurate Peak-Valley and RMS values.

The presence of residual fluid on the surface of a machined component is very common. This is very pertinent in the field of optical manufacturing due to the wide usage of polishing techniques for finishing operations, where the abrasive is normally suspended in a liquid medium.

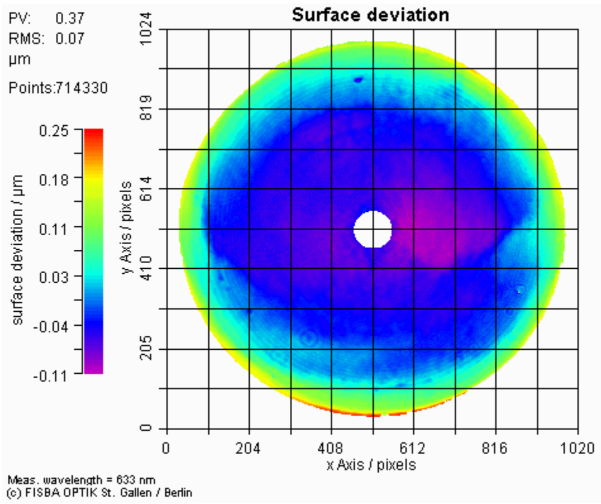

Fig. 8. Contour plot of a cleaned surface

From the above experiment and analysis, we can come to the conclusion that appropriate cleaning and drying of the surface to be measured is of vital importance for the success of in-situ measurements.

This experiment will be further refined in the future to study and quantify the effect of coolant droplets on the accuracy and reliability of the contour plot with respect to droplet size and density.

5. SIMULATION

The Virtual Interferometer is a very helpful tool to determine the contributions of single environmental influences to the measurement error. The examination of a certain error source on a specific measurement is a rather complex matter in a real interferometer since a single error-component can generally not be separated from other effects. However, in a virtual environment this may indeed be observed and closely examined.

It has already be shown, that the Virtual Interferometer can be used to study errors that can not be examined by conventional optical design software [5]. Some error influences, e.g. temperature variations or mechanical stress introduced by unsuited mounting devices, can not be simulated by the Virtual Interferometer itself. But in combination with finite element analysis the effect of these error sources on the measurement uncertainty of interferometrical measurements can thoroughly be examined.

Another important effect on interferometric measurements is vibration. The experiments mentioned above showed a significant influence of mechanical vibrations on the measurement results. Machine vibrations and their influence on the phase-shifting procedure, for instance, can be modelled by averaging several single simulations whereby the position of the optical elements in the interferometer are varied statistically. Fig. 9 shows interferograms which are simulated under different vibration conditions.

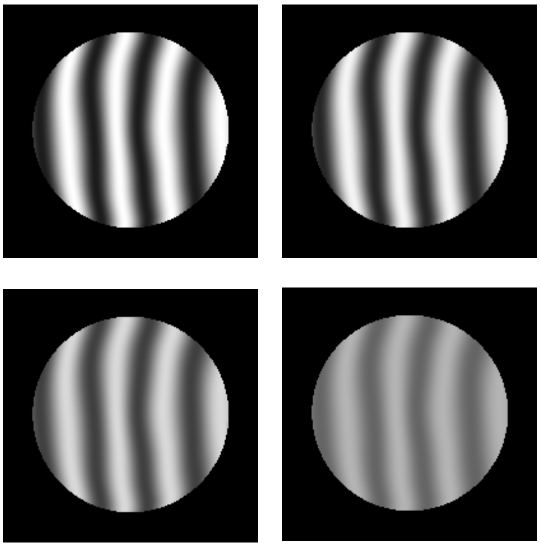

Fig. 9. Interferograms, simulated for different vibration conditions

In these simulation it was assumed that the object under test is vibrating along the optical axis with different amplitudes, since the effect of vibration perpendicular to the optical axis is comparatively negligible. It is known from literature that for vibration amplitudes *A* that are small with respect to the wavelength of light λ, the visibility reduction ΔV is of the order of [6]:

$$\Delta V \approx 1-\left(\frac{A}{\lambda}\right)^2 \quad (1)$$

Like it can be seen in Fig. 10, the simulation show a very good accordance to this formula.

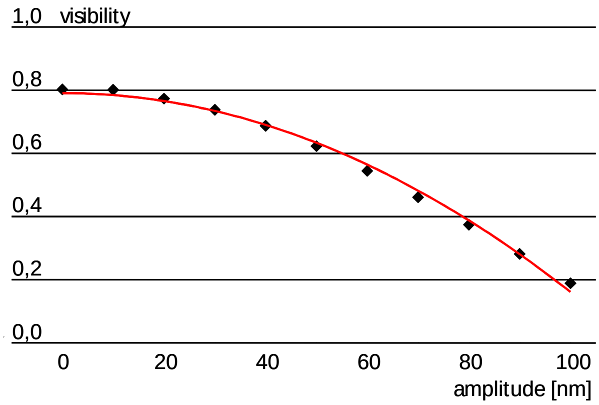

Fig. 10. Visibility for various vibration amplitudes

5. OUTLOOK

In the manufacturing processes of today, a machining accuracy of less than 1 micron is common place. In this scenario, it is necessary for a measurement system to have an accuracy of at least 0.1 microns for it to be deemed as a reliable system. Since the differences between the laboratory measurements and the measurements from the machine were of the order of 0.1 microns, it is clear that the current system is on the limit of this requirement.

In order to make in-situ measurements a practical solution, deeper study needs to be conducted regarding the different factors that contribute to an environment unfavourable to interferometric measurements. Once the factors themselves have been identified, the next step would be to try and quantify the extent to which each of these factors effect the measurement accuracy.

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