TILTED WAVE INTERFEROMETER – DESIGN AND TEST

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ABSTRACT

Requirements on optical systems raise – they need to be more compact with better optical performance. Therefore spherical lenses are more and more replaced by aspheres and freeforms. Both elements can improve the optical performance significantly by more degrees of freedom in optical design. But their manufacturing is complex and needs metrology in the manufacturing process chain. State of the art measurement systems have different disadvantages which limits their usage for aspheres and freeforms. A new interferometric method called Tilted Wave Interferometry can overcome existing limitations. In the paper design and test of an interferometer realizing the new method is described. The Tilted Wave Interferometer is a complex measurement sensor and its function is based on a model based approach. Thus the design process differs from well-known ones. The paper describes these differences and presents results of the development.

Index Terms – Tilted Wave Interferometer, Asphere and freeform measurement, Design

1. INTRODUCTION

Optical systems are indispensable for industrial as well as private use. Demands on such systems raise and the requirements they need to fulfill too. They need to be compact with better optical performance and at the same time less expansive. Therefore more and more aspheres (Fig. 1) are used to replace conventional spheres which lead to smaller optical systems with improved performance [11]. Parallel to this development also freeforms (Fig. 1) find their way into commercial optical systems for example in head up displays of cars [11].

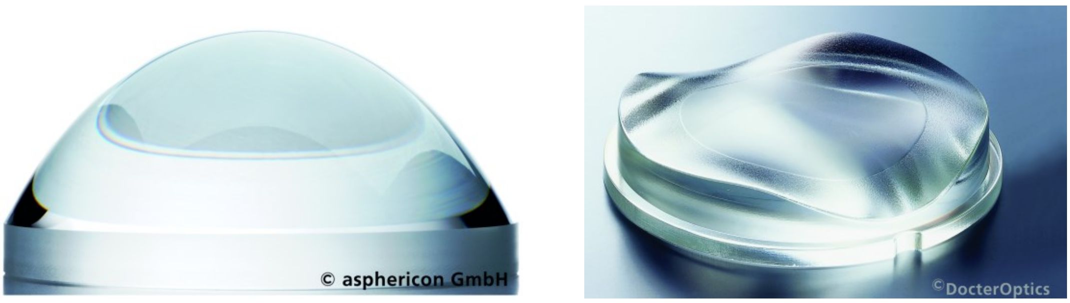

Fig. 1 Example of an asphere (left) and a freeform (right)

Compared to spheres the shape deviations of aspheres and freeforms have larger impact on the overall performance of the optical systems. Thus it is crucial to measure this shape deviation during the whole production process [11] (Fig. 2).

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Contact measurement systems are not suitable for in-process measurement purposes because of their long measurement time and physical contact to the sensitive surface [7].

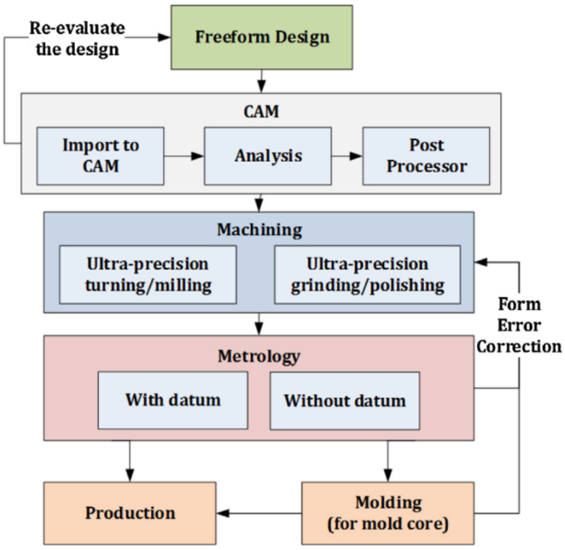

Fig. 2 Manufacturing process chain of freeform optics [11]

Non-contact measurement systems can be separated into two classes: systems with a point sensor and systems with a planar sensor. Systems with a point sensor like confocal microscopy or auto focus probe suffer from their long measurement time. Therefore planar sensors like laser interferometers or phase measuring deflectometers meet given requirements of fast measurement much better. Deflectometry can be used only at surfaces with high reflectivity thus this method is used to measure especially large mirrors [11]. Existing interferometers are mostly Fizeau interferometers with a reference surface. Therefore aspheres and freeforms are typically measured using stitching or Computer Generated Holograms. Thus measurements take long time or they are less flexible and much more expensive because of the productions costs of the Computer Generated Holograms [11].

2. TILTED WAVE INTERFEROMETRY

Tilted wave interferometry is a completely new, patented and flexible method which is able to measure aspheres as well as freeforms [3]. It uses a novel interferometric surface testing principle which was invented at the Institute of Applied Optics at the University of Stuttgart [4][6]. This principle overcomes existing limitations of interferometers because it needs neither reference surface nor stitching if the surface under test fits in the field of view [7]. Therefore it is extremely flexible. Its realization will lead to significant improvements of measurement possibilities and precision. Manufacturers of optical elements need such a method for production control in a closed loop and quality assurance.

2.1 Principle

The Tilted Wave Interferometer is a surface testing interferometer especially for aspheres and freeforms [8][9]. It is based on a Twyman Green interferometer that uses a large number of light sources which are all tilted in respect to each other in a defined manner. Therefore, the device is called Tilted Wave Interferometer (TWI). The availability of manifold light sources in a Twyman Green interferometer allows to measure aspheres and freeform surfaces in a way that is very close to the nulltest setup for spherical surfaces. The idea is that each of the light sources illuminates a part of the surface under test close to a nulltest configuration. In other words, the illuminating rays of the light source are almost perpendicular to a local part of the surface under test yielding a low line density of the resulting interferogram. In consequence, each light source allows measuring a local part of the surface under test. The combination of the interferograms of all light sources enables the measurement of the entire surface under test which is an aspherical or freeform surface (Fig. 3).

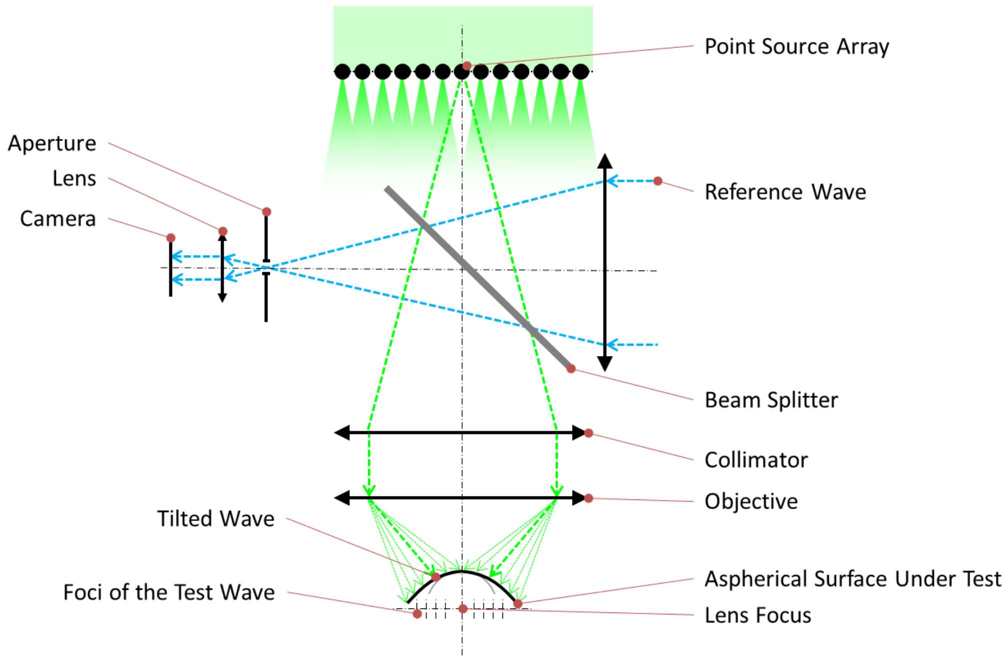

Fig. 3 Principle setup of the Tilted Wave Interferometer with tilted waves measuring an aspheric surface under test

Because of underlying measurement principle the Tilted Wave Interferometer is a complex systems consisting of optics, mechanics, software and control. Its function is realized by a model based approach. A software model describes the ideal optical design of the interferometer. The existing optical design deviates from the ideal one because of different aberrations for example caused by a limited mechanical precision of each component. During a calibration process the existing aberrations are detected and the software model is adapted to the real optical design. Based on this the interferometer is completely described by the software model.

2.2 Measurement

During the measurement of the surface under test several interferograms are captured. Using the target surface description and the model of the real optical design of the interferometer the actual surface deviation can be calculated. Because of its design neither the surface under test nor the interferometer itself needs to be moved for full surface coverage with the different interferograms. The corresponding light sources are partially occluded by moving an aperture array to defined positions thus yielding only spatially separated interferograms (Fig. 4).

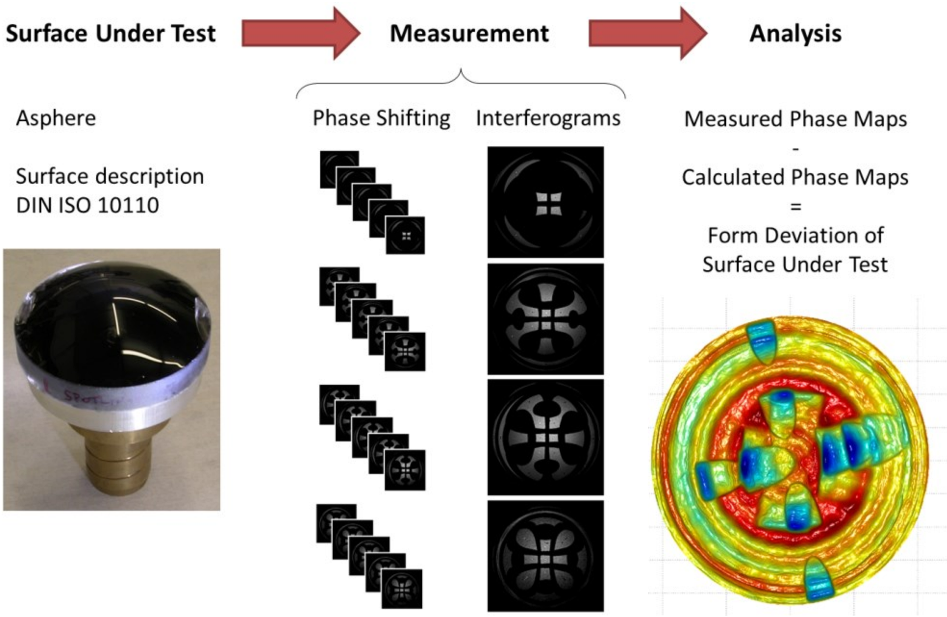

Fig. 4 Principle measurement process of the Tilted Wave Interferometer

2.3 Experimental Setup

A first experimental setup of the Tilted Wave Interferometer was realized at the Institute of Technical Optics at the University of Stuttgart (Fig. 5). It is used to show the function of the interferometric principle and to develop the needed software algorithms.

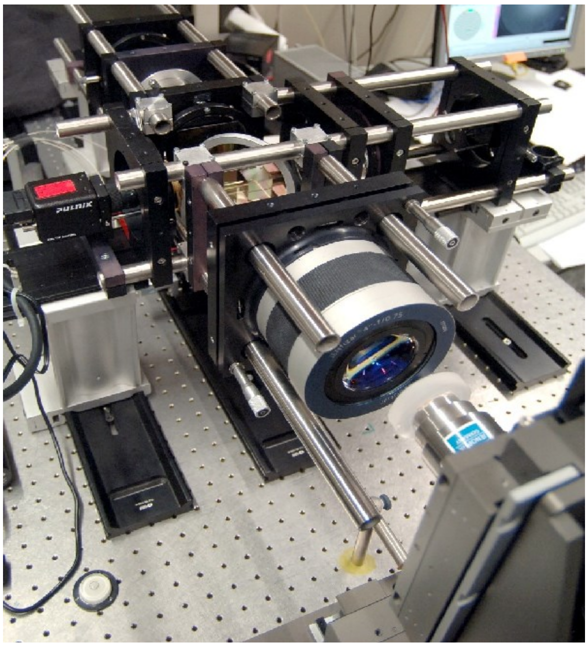

Fig. 5 Experimental setup of the Tilted Wave Interferometer at the Institute of Applied Optics

Few years ago the described measurement principle was not useful for industrial purposes because the model approach and the calibration of the interferometer were to complex and needed too much computer resources in hardware and software. Today this approach can be handled successfully because of much faster hardware and better software tools. It is now possible to describe the optical system with sufficient precision and calibrate it in a reasonable amount of time. Furthermore the measurement and analysis is competitive to existing measurement principles but even more flexible.

Therefore based on the experimental setup and the scientific results at the Institute of Applied Optics at the University of Stuttgart the company Mahr starts to develop a Tilted Wave Interferometer which can be used as an optical sensor in the manufacturing process chain of aspheric and freeform optics.

3. DESIGN

Because of the complexity of the interferometer the design and development of it needs a holistic approach where every engineering field has comparable importance. After the definition of the needed specification the design process of the interferometer is different to typical optical or opto-mechanical systems. Well known design theories and methodologies [5] have their origin in mechanical engineering but to realize the complex function of the Tilted Wave Interferometer also optics, software, electronics and control systems are needed. Furthermore the design does not start with the function model but it starts with a software model which is connected in to an optical design.

3.1 Software Model

The software model is the base for the final measuring system. Aberrations which exist in the optical system of the interferometer need to be described by the model. A model and its used mathematical algorithms can describe an existing system only in a limited way. Therefore the optical system should meet these limitations as good as possible. For the Tilted Wave Interferometer the software model defines properties and requirements of the optical system and its elements for example:

- Wave front distortion of lenses and lens groups
- Optical path length difference between measure and reference wavefronts.

The software model needs to be realized at a very early design stage compared to other optical or opto-mechanical systems. In common systems a software model describes the existing optic or mechanic or electronic setup and is developed later in the design process and is for example used to evaluate the design.

The software model itself is realized here in MatLab which is coupled with an optics design program (ZEMAX). In this way simulations can be made in a closed loop where changes in algorithms can be tested with a virtual optical setup as well as influences of the optical setup on the calculated measurement results.

3.2 Optical Design

Parallel to the software model the development of the optical system takes place. In this step the optical elements are designed or selected and their position is defined and simulated in the optics design program. Here the program ZEMAX is used.

Because of the coupling to the software model it is then possible to simulate the behavior of the interferometer by calculating all wavefronts, resulting interferograms and using a virtual surface under test also measurement results (Fig. 6). Therefore sensitivity analyses of each optical element can be performed before a physical setup exists. In this way optimization of the optical system is carried out. As result a detailed optical design and descriptions of critical optical elements exist. This information includes not only shape, material and tolerances of the optical elements but also their relative positions and needed position tolerances. Thus the optical design is the base for the adjustment strategy and the embodiment design.

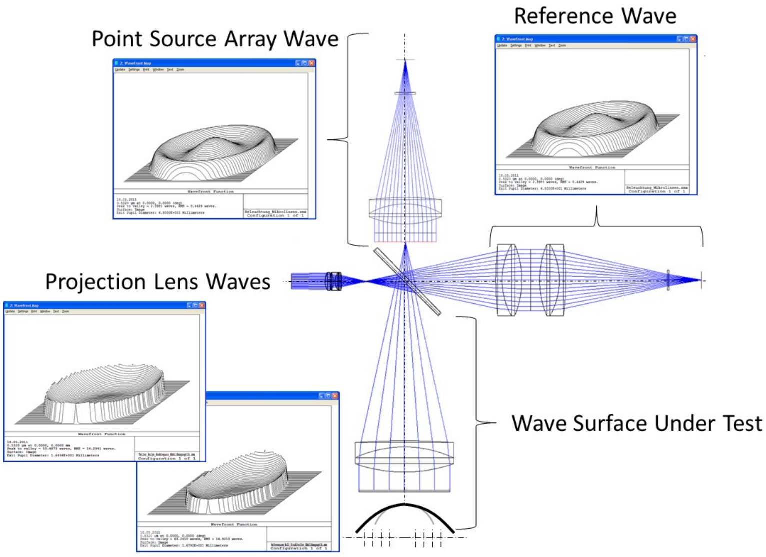

Fig. 6 Optical design of the Tilted Wave Interferometer with resulting wave fronts

3.3 Adjustment Strategy

Before the embodiment design starts it is advisable to define all necessary adjustments and to develop the adjustment strategy. As described above needed adjustments can be derived from the optical design and its simulation. The sensitivity analysis of the optical design shows which position deviations of the optical elements have strong impact on the measuring results. Therefore tolerances of all degrees of freedom can be at least estimated. Thus it is possible to decide if manufacturing tolerances are appropriate or adjustment is necessary. This information can be collected in a preliminary layout of the optical system with described needed degrees of freedom, ranges and tolerances for the adjustment.

The adjustment of mechanical as well as optical elements needs an adjustment base to which every adjustment step can be referenced and also a measurable deviation from a target position (e.g. length) or orientation (e.g. angle). This deviation typically should be minimized so that is smaller than a given tolerance. Auto collimators and sighting telescopes are often used to align elements in position and orientation. They are also used for the adjustment of the Tilted Wave Interferometer in several steps.

The adjustment sequences with the used measurement systems and the deviations to be measured form the adjustment strategy. This strategy can and should be described before the embodiment design exists.

In many cases the adjustment strategy describes which assemblies need to be realized and when they are assembled in the interferometer. Sometimes these assemblies need to be removed again for example to adjust or control a hidden assembly. Therefore the adjustment strategy is a necessary base for the embodiment design to assure that assembly and adjustment of the interferometer are possible in all production as well as lifecycle steps. In the lifecycle of an interferometer adjustment is also often necessary for service purposes. Examples are the replacement of a broken Laser source or a defect camera.

3.4 Embodiment Design

Several boundary conditions need to be considered in the design of the Tilted Wave Interferometer. The following have a lot of impact on the design:

- The Tilted Wave Interferometer is assembled under clean room environment but is used later on under standard environmental conditions which are typical for optics production.
- Furthermore a Laser is used in the Tilted Wave Interferometer with an output of more than 20 mW. Therefore it is harmful to the human eye and additional measures must be taken to avoid any emission outside the interferometer of over 1 mW.
- The Tilted Wave Interferometer is calibrated to determine its optical aberrations. It is supposed that after the calibration every optical element stays in its position and orientation. In reality this assumption cannot be fulfilled because of disturbances like accelerations, vibrations, forces, heat sources and so on. Thus the design needs to be optimized especially with the aim of high mechanical and thermal stability to maximize the time between calibrations.

As result of the adjustment strategy and the boundary conditions a complex embodiment design of the Tilted Wave Interferometer was developed. It consists of several sub-assemblies which have defined mechanical interfaces and can be adjusted separately.

The mechanic is designed under respect of well-known design principles for example to avoid or at least minimize over constrains [1][2]. Therefore the adjustment interfaces consists of ball plane contacts with selected materials. Furthermore all mechanical interfaces of the sub-assemblies are designed highly reproducible with special contact shapes and short and direct force flow to reduce adjustment to a minimum.

All parts used in the Tilted Wave Interferometer are made of materials which are appropriate for clean rooms and can be machine washed. The complete interferometer is covered by stainless steel housing. This housing protects the interferometer and its optical elements against dust and dirt as well as the environment against possible harmful Laser radiation. Furthermore safety shutters inside the interferometer are used as additional safety measures in case the housing is opened without permission.

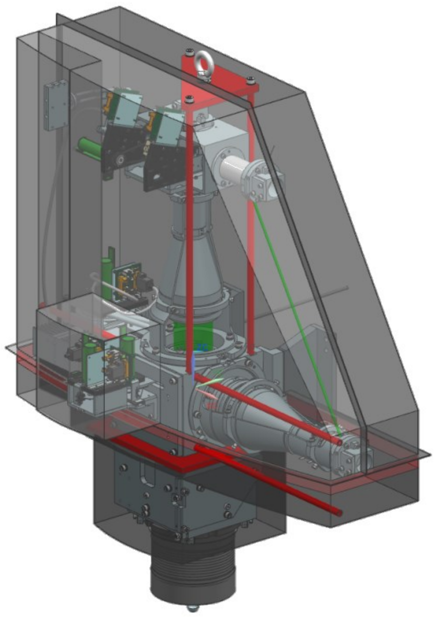

Fig. 7 Embodiment design of the Tilted Wave Interferometer

The embodiment design of the Tilted Wave Interferometer is shown in Fig. 7. For the measurement of optical elements like aspheres and freeforms an additional external frame or positioning unit for larger objects is necessary. Both are realized by Mahr too but not shown here because they are not the focus of this paper.

3.5 Mechatronic System

Parallel to the embodiment design the development of the mechatronic system takes places. To operate the Tilted Wave Interferometer several apertures and shutters need to be positioned. Thus the interferometer consists of many mechatronic elements too. Furthermore a precise and repeatable relative positioning of the calibration object to the interferometer is necessary. Also the surface under test needs to be aligned to the interferometer (Fig. 8).

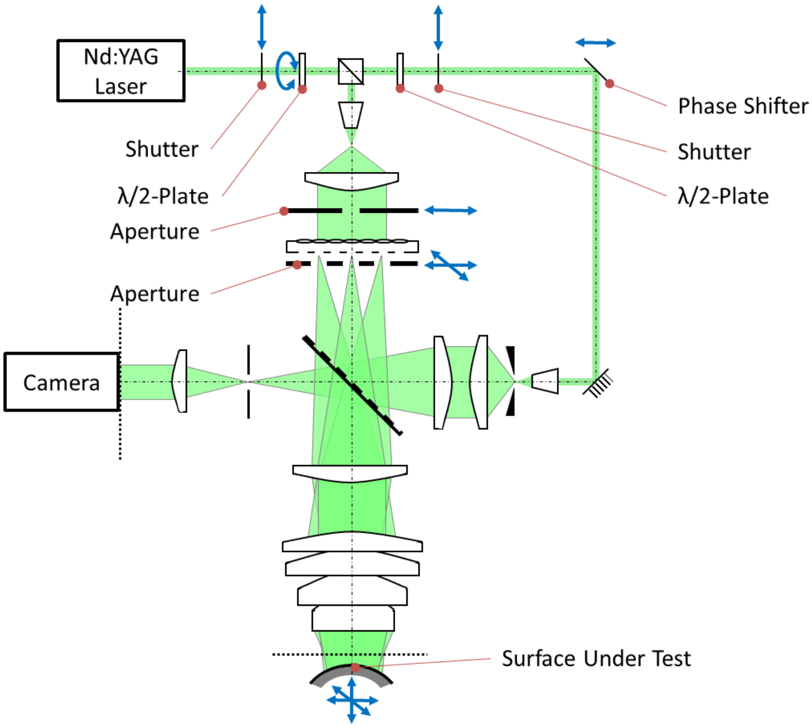

Fig. 8 Mechatronic elements of the Tilted Wave Interferometer and their degrees of freedom

Integrated in the housed interferometer are two electromagnetic shutters, two with dc-motors motorized apertures and one phase shifting piezo drive. All drives are connected to the main control system outside the interferometer via cables and have specified and uniformed electronic interfaces. These interfaces establish a modular concept which supports production and service of the mechatronic elements. A camera with four mega-pixels is used to detect the resulting interferograms.

The drives as well as the camera are heat sources. Therefore additional measures are taken to decouple the heat sources from the optical elements and their mechanical fixtures. Furthermore heat pipes and heat sinks are used to conduct heat outside the interferometer.

To calibrate the Tilted Wave Interferometer a calibration object – a sphere – is positioned in several positions in three dimensions in a range of about 20x20x10 mm^3 relative to the interferometer. These positions are defined by the optical system and the software model. The reference position is interferometrically measured with the center source of the Tilted Wave Interferometer. All following positions are related to this position. The tolerances of these positions have influence to the final measurement accuracy and should be less than a few micrometers as a three dimensional deviation. Therefore this positioning unit needs high accuracy and repeatability and should be thermally stable because the calibration takes several minutes. A commercial three dimensional positioning unit with piezo-steppers and linear ball guides is used (Fig. 9). The mechanical design and the actuators have great impact towards reaching the needed positioning accuracy. Several tests showed that the control parameters play an important role too.

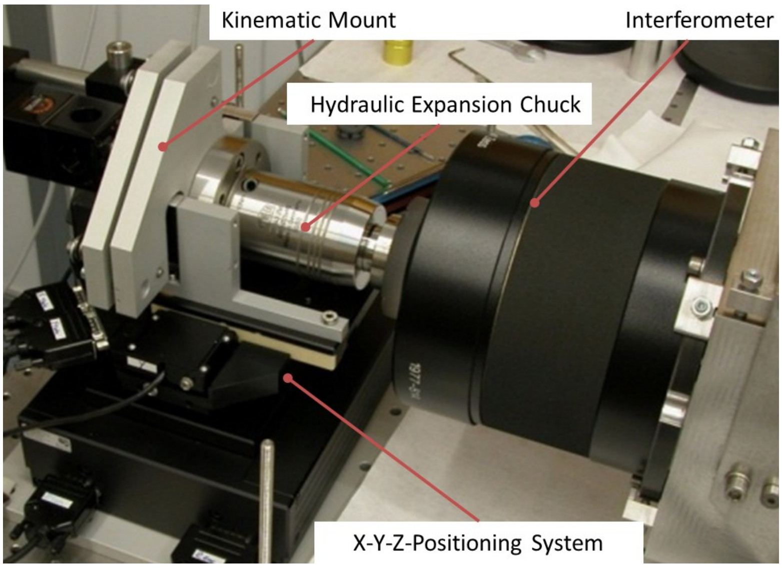

Fig. 9 X-Y-Z-positioning unit with kinematic mount and hydraulic expansion chuck in front of Tilted Wave Interferometer

On top of the positioning unit a fixture for the object with the surface under test is mounted (Fig. 9). This fixture is a commercially available hydraulic expansion chuck. It clamps the shaft on which the object is glued to in a typical optical production processes. The shaft is the base for the orientation of the surface under test. Because of tolerances between the shaft and the surface under test as well as test purposes the surface under test need to be adjusted. Two rotational freedoms perpendicular to the optical axis of the interferometer are necessary. They are realized by a custom kinematic mount.

3.6 Control System

After the definition of the mechatronic elements their integration and optimization is realized. As described above for the calibration of the Tilted Wave Interferometer itself as well as for the measurement of the probe under test accurate and repeatable positioning is essential. The used positioning unit consists of three axes: X and Y as horizontal axes and Z as vertical axis. Because there is no calibration of the axes a calibration needs to be realized before the desired accuracy in three dimensions can be reached. Furthermore the control parameters need to be optimized too because position stability and position rest need to be in the sub-micron range.
At first the properties of all axes were checked with an external laser interferometer system (Renishaw ML10 Gold). To test the system under comparable operating conditions the hydraulic expansion chuck which holds the calibration object or the object with the surface under test is mounted on top of the positioning unit.

After this the control parameters were optimized using a model based approach (Fig. 10). With this approach it was possible to significantly minimize the range between the lowest and the maximum value. Thus position rest and repeatability were improved and the optimization was successful.

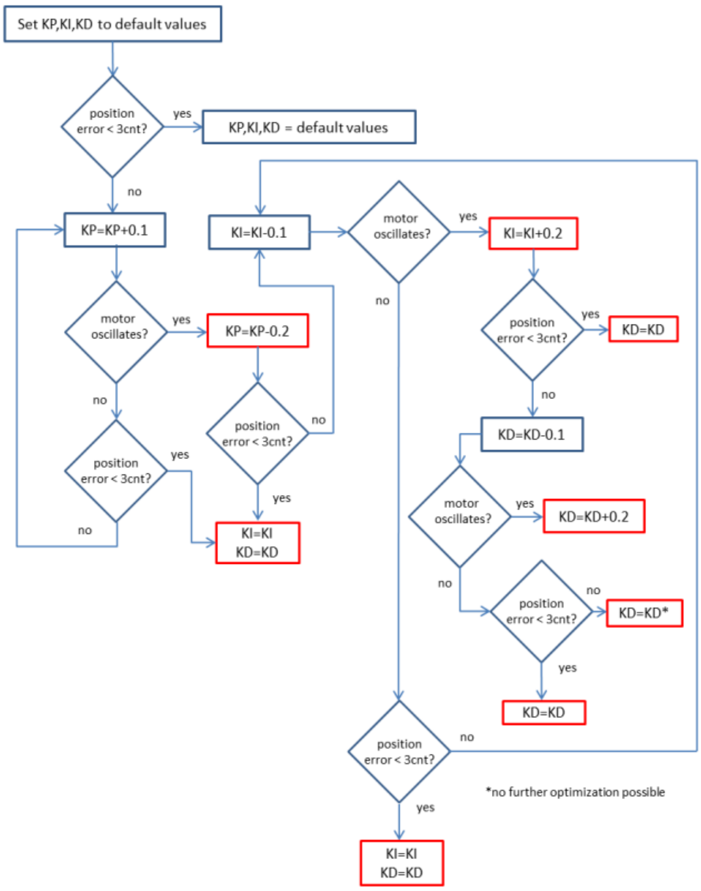

Fig. 10 Workflow for setting PID parameters of the X-Y-Z-positioning unit

Furthermore using the laser interferometer every axis was measured at its complete moving range with the optimized control parameters several times. A high point density is the base for the adjustment function. Here a spline is approximated to the measurement results. This spline is used for a supporting point calibration. Therefore a lookup table is used to correct the source position so that the desired target position can be reached better than 1 µm. Positions between two supporting points are interpolated. The lookup table and the needed algorithms are not implanted in the controller of the positioning unit but in the PC and software of the Tilted Wave Interferometer. Thus it is very flexible and a further coordinate transformation can be integrated too. After the calibration the residual error is reduced significantly.

4. ASSEMBLY AND ADJUSTMENT

4.1 Horizontal setup

At first a horizontal setup of the Tilted Wave Interferometer is realized in the clean room (Fig. 11). It is assembled on a vibration damped bread board without housing. Thus it is possible to test for example the reproducibility of mechanical interfaces or the adjustment and to make easily changes to the optical system if needed. Furthermore this setup is used for software development and experiments with different calibration objects.

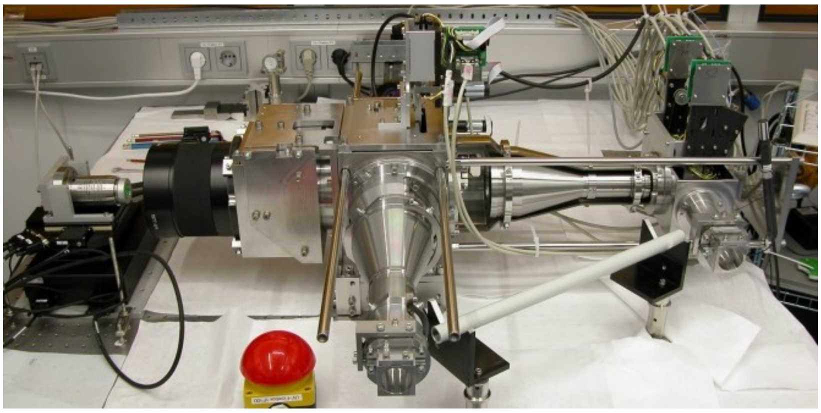

Fig. 11 Horizontal setup of the Tilted Wave Interferometer with X-Y-Z positioning unit on bread board

Assembly and adjustment take place simultaneously. At first a coarse adjustment is realized where all optical elements are aligned to the defined optical axis of the Tilted Wave Interferometer. Then the interferometer is put into operation with Laser source and camera online. Using a highly even plane mirror in front of the Tilted Wave Interferometer the first interferogram can be recorded if the coarse adjustment meets the designed optical system sufficiently. This interferogram is used for the fine adjustment. The aim is to adjust the optical system in a way that the simulated interferogram out of the software model is met with only minor deviations. Shown in Fig. 12 these steps are performed with the horizontal setup successfully. After this the calibration of the Tilted Wave Interferometer can be started.

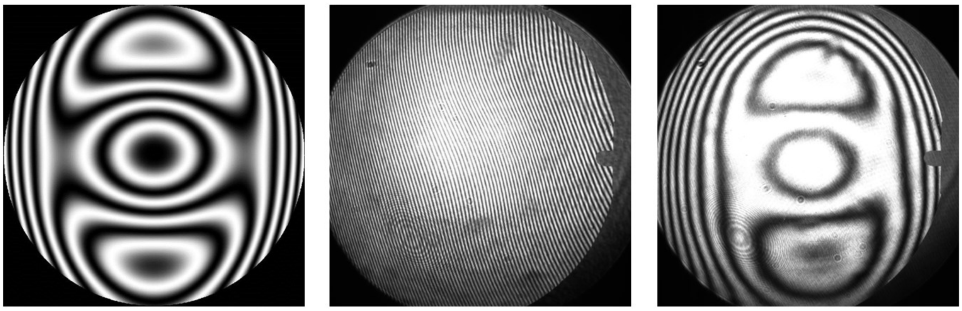

Fig. 12 Interferogram of a plane mirror in front of the Tilted Wave Interferometer, simulated (left), after coarse adjustment (middle) and after fine adjustment (right)

4.2 Vertical setup

The vertical setup is much more complex compared to the horizontal. It consists of a completely housed Tilted Wave Interferometer, a long range positioning unit made by Mahr to measure larger optical elements and the above described X-Y-Z-positioning unit. The complete measurement system stands on a vibration damped base (Fig. 13).

The vertical setup meets the needed requirements for the measurement in the production process chain of aspheres very well. It can be used in common environments of the optics production and has a user friendly workplace.

The first vertical setup is used in the EMRP Project IND10 by colleagues at the Physikalisch-Technische Bundesanstalt at Braunschweig to evaluate the Tilted Wave Interferometry and realize a metrological feedback for aspheres and freeforms [12].

Fig. 13 Vertical setup consisting of Tilted Wave Interferometer, combined long range and X-Y-Z-positioning unit, control system and work place

5. TEST

5.1 Mechanical Properties

The mechanical properties especially stiffness and thermal stability play a major role for the accuracy and robustness of the Tilted Wave Interferometer. Therefore the mechanical setup is designed carefully to meet the given requirements.

For the verification of the mechanical properties of the horizontal and for the vertical setup several tests are made. For example the mechanical stiffness is tested using a laser interferometer to measure the vibrations between Tilted Wave Interferometer and hydraulic expansion chuck. The impulse response of the setup is measured for different stimulations and axes.

As result typical Eigen frequencies of both setups are detected. These Eigen frequencies include the complete measurement circle. Nevertheless several frequencies are found at both setups and can be traced back to the Tilted Wave Interferometer itself. They are in a range which shows that the mechanical stiffness of the interferometer is sufficient for its purpose. Additional test were conducted to prove the thermal stability and mechanical reproducibility. As result it was possible to show that several weeks between the calibrations of the Tilted Wave Interferometer are possible without significant loss of measurement accuracy.

5.2 Measurements

Several aspheres are used to show the performance of the Tilted Wave Interferometer. The most interesting measurements are those with measurement data of different measurement systems. For this purpose a demonstrator asphere was realized by the Institute of Technical

Optics at the University of Stuttgart. This asphere can be measured by state of the art measurement systems. Thus the measurement results can be compared (Fig. 14).

Asphere A5	
Clear aperture	50 mm
Best-fit radius	40.8 mm
Best-fit deviation	600 µm
Gradient deviation	8°

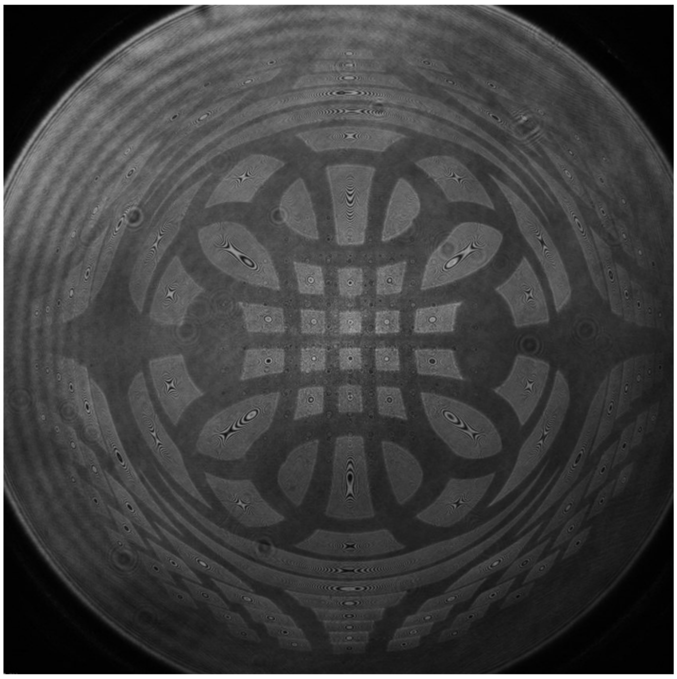

Fig. 14 Demonstrator asphere A5, nominal data and interferogram

Furthermore the asphere has fabrications marks realized by magneto rheological finishing. These marks are unwanted fabrication errors but have the advantage to be unique and easily detectable.

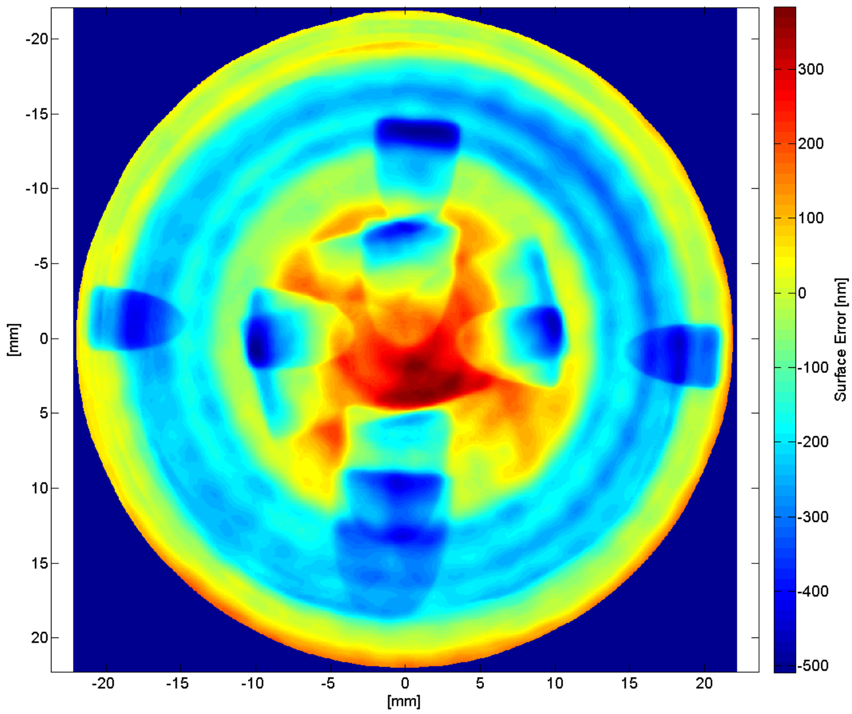

Fig. 15 Measured surface error of demonstrator asphere A5 measured with Tilted Wave Interferometer

The asphere is measured with every Tilted Wave Interferometer. No additional relative positioning between asphere and interferometer during the measurement process is necessary.

Thus the measurement itself takes less than one minute and is very stable and reproducible. The measurement result shows surface error of the asphere (Fig. 15). It includes long-wave form deviations of the asphere from its desired form. Because of the high lateral resolution of the Tilted Wave Interferometer also short-wave surface errors can be seen in the measurement result. Measurements of other state of the art measurement system showed comparable results. Therefore the function of the Tilted Wave Interferometer was successfully approved [12].

6. CONCLUSIONS

The Tilted Wave Interferometer is a complex opto-mechatronical system and its function can only be realized by the software based model approach. Thus its design process differs from well-known systems especially those who are described in the design methodology and theory [5]. The paper presents this design process and its successful application by realizing a completely new interferometric measurement sensor.

The used design process results from the requirement to realize a robust Tilted Wave Interferometer in an industrial environment with the aim to satisfy customer needs. Thus aspects of time to market, development and product costs, manufacturing processes and limited resources dominate.

Nevertheless the developments in the field of computer science lead to more and more complex systems. Complex means in this context that only the successful cooperation of different sciences lead to a product. They consist of mechanics, electronics, mechatronics, optics and software. But software is not only used as user interface or control system. Software is the virtual representation of physical and mathematical relations. Today it becomes the core function of such systems and the physical elements are designed to fit to the software and its model.

Therefore these aspects need to be further integrated in the design process and its methods. The design process is not a separate one for mechanics, electronics, mechatronics, optics and software. It is interdisciplinary and needs a holistic approach.

7. OUTLOOK

The current development state of the Tilted Wave Interferometer measurement system shows its capability to measure aspheres successfully. Nevertheless further steps are necessary to verify the new interferometry principle together with partners at the Institute of Technical Optics at the University in Stuttgart and the Physikalisch-Technische Bundesanstalt in Braunschweig with the aim to offer customers a product for the measurement of large aspheres and freeforms [10]. Tests showed that freeforms can be measured with the Tilted Wave Interferometer without changes of the optical or mechanical setup (Fig. 16). Thus the next development steps will be also focused on the adaption of the positioning unit for larger objects (Fig. 16). They need more degrees of freedom in the positioning because stitching is necessary to cover the whole surface.

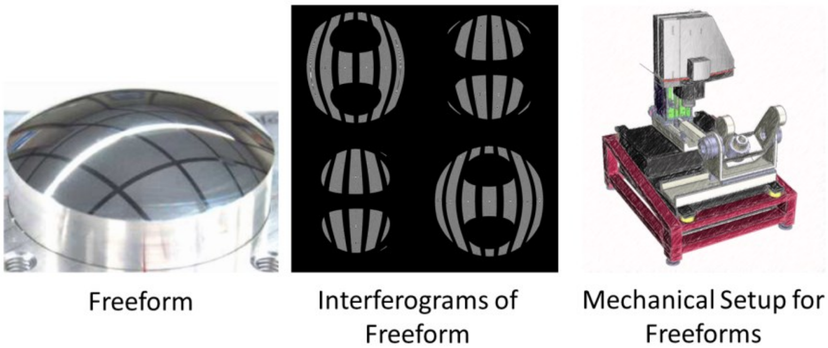

Fig. 16 Freeform object (left) with simulated interferograms (middle) and preliminary design of mechanical setup for measurements of freeform (right)

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