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Determination and compensation of the ''reference surface'' from redundant sets of surface measurements

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ABSTRACT

When trying to measure an optical surface at utmost absolute precision, the problem of the missing or unknown ''reference surface'' is often encountered. It is obvious with Fizeau and Michelson's interferometry, where the height difference between the surface under test (SUT) and a reference surface is measured. It is also true from slope measurements in long trace profilers (LTP), where due to small construction errors, the response to a perfectly flat ideal surface can be considered as an unknown reference to be subtracted from the measurement data. As no ''perfect artifact'' can exist, these references cannot be directly determined. The addition of the unknown reference can severely bias the reconstructed surface when field stitching is applied.

The results of ptychography have proved that when a measurement is a function of a unique object function with a translated but unique response function, the redundancy of a large set of data allows accurate reconstructions of the object and response function despite the presence of measurement noise. In the case of LTP and interferometry, the basic problem is linear and can be solved by linear algebra rather than iteratively. The method has been already applied to SOLEIL and ESRF LTPs and is succesfully used on a regular base. We show here that the method can be also applied to interferometry and improve stitching results.

1. Introduction

Quality of an optical surface is evaluated from the departure of the surface from an ideal optimal shape. Progress of optical surface polishing techniques is such that local correction of less than 1 nm in height can be reliably applied. However asserting a shape error with an accuracy below 1 nm is not an easy task because shape measurements are never absolute.

Two different kinds of instruments are used for measuring the shape of optical surfaces, interferometers and slope profilers. Interferometry is relative by nature, since the measured quantity is the height difference between the surface under test (SUT) and a reference surface. Slope profilers are measuring the angular deviation of a probe beam which is scanned on the SUT along a line. Different schemes are used, but the angle measuring part is typically an autocollimator head. At the microradian level, the linearity of the angle response can no longer be assumed, because inhomogeneities in the glass of the autocollimator lenses produce small spurious deviation depending on the position of the returning beam. Moreover, as the beam return path depends on the travel distance from the autocollimator to the SUT this calibration is valid for a defined travel distance.

In order to recover the ''true surface'', the reference surface, or the slope calibration curve, need to be determined with the same accuracy. This determination is difficult because straightforward methods, such as measuring a perfectly known surface or tilting a surface with perfectly known angles, is not possible. When using an interferometer, a classical way to turn around the difficulty is to average random areas of a good quality surface larger than the field of view. The solution is a good starting point, but since the statistical properties of the surface are not known there is a good chance it introduces bias, especially for the lowest spatial frequencies.

The method that we investigate here is an extension of this method in the sense that we use repeated overlapped measurements of the same surface at different relative positions of the reference with respect of the surface or at different tilt angles along the calibration curve. As a result we obtain a redundant set of measurements which contains information of both the SUT and the reference (or SUT slope profile and calibration curve). For profiler type measurement we already showed in a previous paper [2] that it was possible to recover both the surface slope and the calibration curve. More examples on this are given here. We also show that the application of the same redundancy principle to interferometric measurements allows recovering both the SUT shape and the reference.

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2. Solving the reference problem from redundant overlapped measurements

Let us assume that we have a measuring procedure whose result, $\mathbf{M}(x_{i,j})$, recorded on a pixelated detector, is the sum of the true surface signal, $\mathbf{S}(x_{i,j}+x_0)$, a reference signal $\mathbf{R}(x_{i,j})$ which depends on the position x. The measurement can be repeated while changing the (known) offset x_0 between the object and the reference. So doing, datasets $\mathbf{M}_k(x_{i,j})$ are being built where the point to point coupling between the signal and the reference is each time different. Neglecting measurement errors, we have

$$\mathbf{M}_k(x_{i,j}) = \mathbf{S}(x_{i,j}+x_k) + \mathbf{R}(x_{i,j}). \tag{1}$$

Since the two vectors $\mathbf{S}$ and $\mathbf{R}$ are unique we are getting a redundant information on them. In more mathematical terms, we are building a large set of overdefined linear equations which can be only solved in a least square sense. In other words we can look for $\mathbf{R}(x_{i,j})$ and $\mathbf{S}(x_{i,j})$ such as the total error $E = \sum_k [\mathbf{M}_k(x_{i,j}) - \mathbf{S}(x_{i,j}+x_k) - \mathbf{R}(x_{i,j})]^2$ is minimum. It is a maximum likelihood regression (MLR). The convergence of the minimization of error E, actually means that the reproducible and consistent information on the signal $\mathbf{S}$ and reference $\mathbf{R}$ can be extracted and separated from other sources of deviation included in the data. The residuals, $\mathbf{M}_k(x_{i,j}) - \mathbf{S}(x_{i,j}+x_k) - \mathbf{R}(x_{i,j})$ are the statistical errors inherent to measurements mixed with other sources of deviation not included in the model. When one of these deviation sources can be modeled as depending linearly of a set of extra parameters P_n such as the tip tilt of the reference with respect to the SUT, they can be included in general equations and extra parameters P_n are also determined together with $\mathbf{S}$ and $\mathbf{R}$.

In the thought experiment defined above, it is assumed that the translation steps x_k are integer numbers of pixels and each equation is relating one point of the signal to one point of the reference. The matrix of the equation system is therefore very sparse and well conditioned for iteratively solving the least square problem. It may happen that step sizes x_k are not integer pixel size and that the value of function $\mathbf{R}$ or $\mathbf{S}$ needs to be interpolated at the measurement position from the grid of computation values. In order to preserve the equation matrix sparseness, the interpolation function should be local and involve only a minimum number of data values. This is especially important when the size of the problem is larger.

As in any MLR method, the convergence of the error minimization toward a reasonable solution is not guaranteed and depends on the validity of the model used. When iterative computation methods are used, it depends also on the equation conditioning and on the quality of the starting point approximation. However it should be reminded that redundancy and MLR methods are currently used for solving problems of object recovery from entangled data in much more complicated cases than the simple addition of two functions. A noteable example is ptychographic imaging which allows recovering both the object and probe function from overlapped far field diffraction images of the probe and object product [1].

3. Application of redundant overlapped measurements to LTP

As said in Section 1, the response of the long trace profiler (LTP) of SOLEIL presents slight (few microrads) nonlinearities over its 8 mrad measuring range, and hence, as any instrument of its kind, it needs to be calibrated. Moreover, since the distance between the SUT and the slope measuring head can have large variation, this calibration may substantially differ from one measurement to another. The overlapped redundant measurement method, allowing to simultaneously obtain the SUT profile and the linearity error, has been quite systematically used at SOLEIL since it was developed a few years ago under the name LEEP (linearity error elimination procedure) [2]. The method is usually applied as a stitching method for strongly curved surfaces when the slope range exceeds the 8 mrad measuring range of the LTP. The surface is placed on the LTP bench and tilted in such a way that one extremity of the mirror is measured at the center of the LTP measuring range and a profile measurement is made on the part of the mirror which can be measured. Then the mirror is tilted step by step until the other end of the mirror is also measured at the center of the measuring range. Profiles are recorded at each step on the measurable part of the surface. Tilts steps are chosen so that any position x of the SUT is measured with enough redundancy (20 times whenever possible).

Denoting the linearity correction for the measured slope, s, by $C(s)$ and the tilts by $\mathbf{T}_k$, the recorded slope data can be described as

$$\mathbf{M}_k(x_i) = \mathbf{S}(x_i) + \mathbf{C}(\mathbf{M}_k(x_i)) + \mathbf{T}_k \tag{2}$$

where it is assumed that the SUT is short enough for the error coming from the change of the return path being negligible with respect to the slope induced correction $C(s)$. For solving the problem, the linearity correction needs to be evaluated on a grid of tabulated slope values s_p and therefore the correction for a given measured slope $s = \mathbf{M}_k(x_i)$ must be interpolated on this base in a form such as

$$C(s) = \sum \mathbf{B}_p(s)\mathbf{C}_p. \tag{3}$$

As mentioned before, the interpolation should be local to preserve the sparseness of the equation matrix. In our implementation we use a cubic B-spline interpolation for which the at most 5 coefficients $\mathbf{B}_p$ are non zero for any s. With this interpolation, the system of Eq. (2) can be rewritten as a set of linear equations of the unknown vectors $\mathbf{S}(x)$, $\mathbf{C}$, and $\mathbf{T}$, and, since this system is overdefined, it can be solved in a least squared sense as stated before. The LTP correction problem is one-dimensional and therefore remains small enough to be solved on a personal computer.

At Soleil, the method is applied to all surfaces for which stitching is required and when the utmost accuracy is needed. It was also successfully applied to ESRF LTP measurements [3]. The spherical test mirror ($\mathbf{R}$=9.3113 m) the shape error of which is given in Fig. 1 is a typical example. This strongly curved mirror has been circulating between synchrotron laboratories for mutual comparison of their measuring instruments. Fig. 1 is plotted with the height errors of this mirror as measured by the Hemoltz Zentrum Berlin (HZB)/Bessy II NOM [5], by ESRF LTP without application of the LEEP method and by SOLEIL LTP with application of the LEEP method. The agreement between SOLEIL LTP and

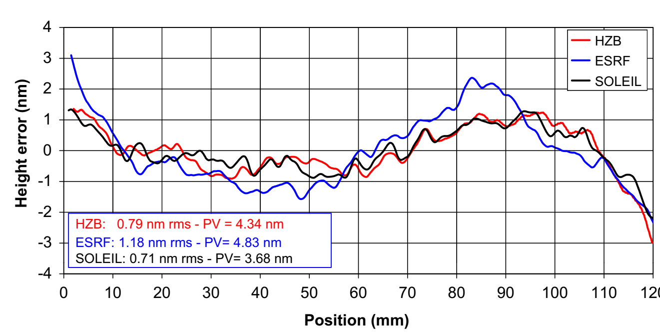

Fig. 1. Height errors of a 9.3 m spherical reference mirror resulting from measurements made at HZB-Bessy, ESRF and SOLEIL. Linearity errors of HZB NOM are compensated by precise calibration at PTB, those of SOLEIL LTP are corrected by application of the LEEP method, while ESRF data are uncorrected. (Courtesy Franck Siewert and Amparo Vivo.)