Scanning phase shift interferometry in length measurement

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1 Introduction

At PTB a new setup is under development for measurements of the absolute length of samples at cryogenic temperatures down to 10 K [1]. For this reason the Ultra-Precision Interferometer (UPI) [2] was equipped with an external measuring path which can be cooled by liquid nitrogen or by a pulse tube cooler. Due to the cooling measures vibration is provoked in the interferometer system. Furthermore, since the cooled part of the interferometer is a separate extension to the stabilized vacuum chamber, temperature changes can lead to a drift of the length of the beam path.

In length measurements by interferometry the common phase stepping algorithms mostly require fixed and well-known phase steps between the recorded interferograms. Hence, in the presence of unstable conditions in the environment of the experiment phase shifting interferometry cannot be performed as usual. Therefore, Vikhagen [3] developed the so-called scanning phase shift technique for the application of electronic speckle pattern interferometry in deformation measurement under unstable environmental conditions.

In this paper we present an extension of the original approach in order to use the technique for interferometric length measurements.

2 The SPS principle

Unlike other evaluation algorithms the phase can be extracted from one single interferogram in a series of frames in which the phase steps may vary from frame to frame. When the phase is shifted continuously or step by step while the series is recorded (simulated example in figure 1), the intensity at each pixel varies between the minimum and the maximum value which is described for a two-beam interference by the expression:

$$I(x,y) = I_O(x,y) + I_A(x,y)\ \cos[\varphi(x,y)]\,. \tag{1}$$

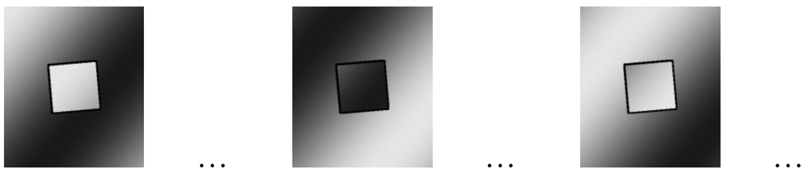


Figure 1: Three exemplary interferograms taken from a series of simulated intensity frames. The small square in the centre represents a gauge block sample which is wrung on a platen.

In this equation I_O is the bias intensity, I_A is the amplitude and φ is the interference phase. Provided that each of these arbitrary phase steps is a small fraction of one interference order, the minimum and maximum intensity values can be detected pixelwise over the whole series of interferograms yielding the intensity offset

$$I_O(x,y) = \frac{I_{min}(x,y)+I_{max}(x,y)}{2} \quad (2)$$

and the modulation amplitude

$$I_A(x,y) = \frac{I_{max}(x,y)-I_{min}(x,y)}{2} \quad (3)$$

of the measured interference (figure 2).

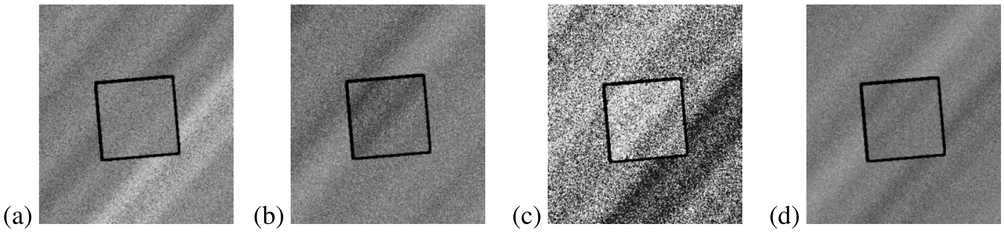


Figure 2: (a) minimum intensity per pixel of the whole series; (b) maximum intensity per pixel of the whole series;(c) intensity offset; (d) amplitude [note: each image is normalized to the full greyscale]

Finally, the phase related to the interferogram $I(x,y)$ is

$$\varphi(x,y) = \arccos\left[\frac{I(x,y)-I_O(x,y)}{I_A(x,y)}\right]. \quad (4)$$

In order to resolve the sign ambiguity of the arccosine function a second frame $I_s(x,y)$ is involved in which the phase differs only by a small amount from the other one. From the investigation of the intensity differences $I(x,y) - I_s(x,y)$ a correction of the phase quadrants can be performed pixelwise. Due to random noise in the intensity data the accuracy of the calculated phase is affected. This especially applies to the pixels where the phase is close to π or 2π, i.e. when $I(x,y)$ is close to $I_{max}(x,y)$ or $I_{min}(x,y)$. The corresponding pixels are omitted from the phase evaluation leaving a gap in the phase map (figure 3(b)). The size of the gap depends on the width of the interference fringes which is influenced by the parallelism and the flatness of the surfaces under inspection.

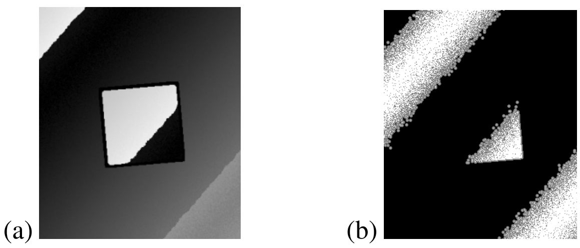


Figure 3: (a) Exemplary phase map modulo 2π. (b) The bright area in the binary mask indicates the pixels with unreliable phase values.

3 SPS in length measurement

3.1 The procedure

The gaps in the phase maps may lead to the situation that too few or no reliable pixels are available for the determination of the length. Therefore, we developed a modification of the original approach of Vikhagen taking into account the whole series for the phase determination which is described in the following.

A series of interferograms is recorded while the phase is shifted in small steps (as in figure 1). But instead of using only one intensity frame for the phase determination, the phase is evaluated for each of the frames in the whole series involving the respective subsequent frame for resolving the sign ambiguity. Thus, the gap with unreliable phase values is located at another position in different phase maps (figure 4).

Figure 4: Two exemplary binary masks indicating the pixels with unreliable phase values in two different phase maps.

Then one frame in the middle of the series is defined as a reference and the phase differences between this reference and the other frames are calculated pixelwise in the regions where no unreliable phase values are located (figure 5). Provided that the surfaces under inspection do not change their topography while the phase is shifted, the phase difference of each frame related to the reference is quasi-constant over the whole image (except for the effect of a sample tilt during the measurement) and can be determined as an offset by fitting a plane to the respective difference values.

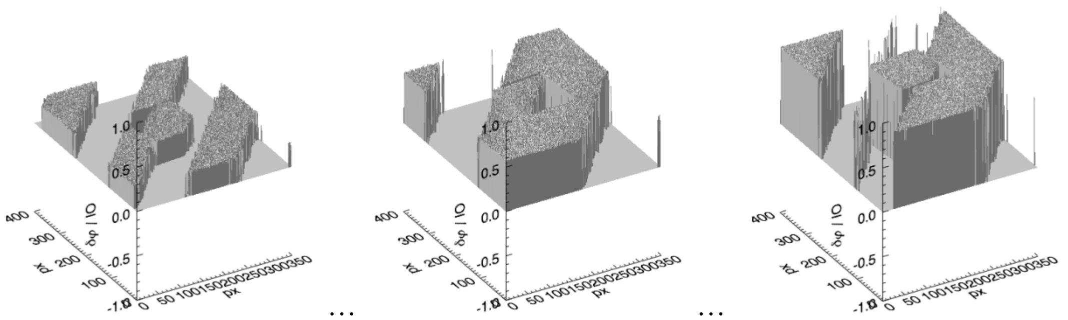


Figure 5: Phase differences of three exemplary phase maps related to the reference frame. Only the reliable pixels of the respective frames are considered.

Figure 6 shows the mean reference offset $\delta\varphi_n$ of each frame as a fraction of one interference order (IO). The offset is zero for the reference frame. It can be seen from the course of the data points that the steps between the frames are not equidistant. In this simulation the step size varied randomly between 0 and 10 % of an interference order.

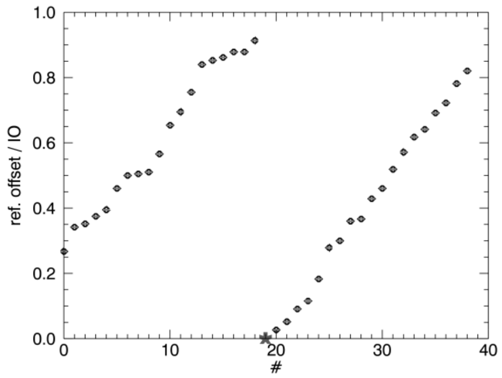


Figure 6: Mean reference offset for each frame as a fraction of one interference order.

Finally, an amended phase map is calculated by the pixelwise average of the reliable regions of all phase frames involving the respective offset correction $\delta\varphi_n$. In the case of *N* intensity frames, we get *N-1* phase maps. The amended phase map is then given by the expression

$$\varphi = \frac{1}{N-1}\sum_{n=1}^{N-1}\left(\varphi_n - \delta\varphi_n\right)_{\mathrm{mod}\,2\pi} \tag{5}$$

and free of gaps (figure 7). For the calculation it has to be taken into account that all phase values are known modulo 2π. In this phase map the phase difference between the sample and the reference plate can be determined for the usual length evaluation which is described in the following section.

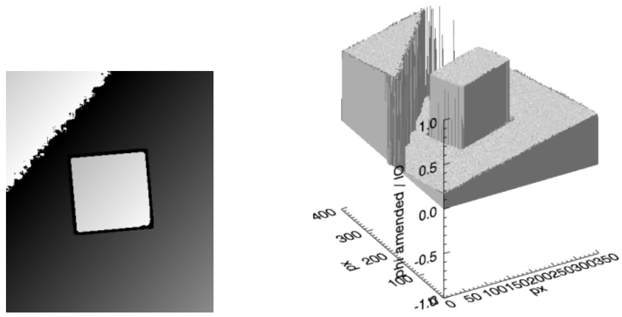


Figure 7: Amended phase map modulo 2π calculated by the modified SPS technique on the basis of 40 simulated intensity frames.

3.2 Preliminary experimental result

As an example we demonstrate the procedure with a real silicon carbide sample wrung onto a silicon reference plate (figure 8). Therefore, in the UPI setup at room temperature a series of 50 interferograms was recorded by the camera, while the phase was shifted monotonically with a randomized step size by a piezo actuator. For each intensity frame the phase is determined pixelwise by means of equation (4) together with the corresponding binary mask of unreliable values and the related standard uncertainty. The latter is calculated following the GUM [4]. By use of equation (5) the amended phase map is calculated from the whole series of phase maps. In this calculation only the left sample and the reference plate is considered. Figure 9(a) shows the phase distribution modulo 2π.

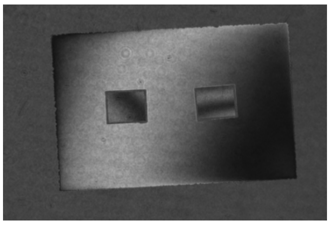
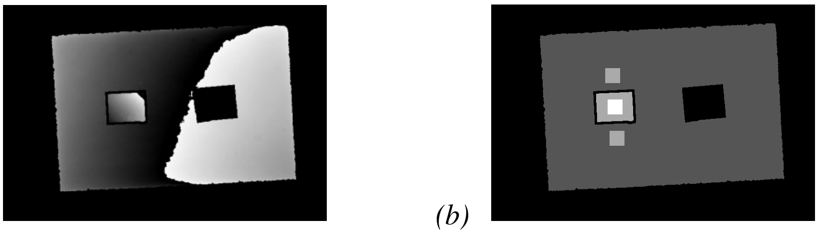


Figure 8: Exemplary interferogram of two silicon carbide samples with polished faces wrung onto a silicon reference plate. For the demonstration of the evaluation the left sample with the better parallelism (less fringes) is chosen.



(a) *(b)*

Figure 9: (a) Amended phase map without gaps. (b) Regions of interest (the three small bright squares) for the length evaluation.

Then based on the amended phase map the fractional order of interference of the sample's length can be determined. Therefore, the pixels in selected regions of interest beside and on the sample (figure 9(b)) are averaged and the phase difference is calculated by the expression

$$\Delta\varphi = \varphi_s - \frac{\varphi_1 + \varphi_2}{2} \tag{6}$$

with φ_s as the mean phase on the sample and φ_1 and φ_2 as the mean phase beside the sample. By repeating this procedure with different wavelengths one can determine the absolute length of the sample ("method of exact fractions"). The statistical part of the uncertainty of the current example amounts to approximately ± 2.4 nm. The result is validated by a comparison to the length which was determined with the usually applied phase shifting technique [5] at stable conditions. The values coincide within their uncertainty range.

4 Conclusion

Since the actual measurements are still running, this paper gives an overview of the basic principle of the procedure. With the presented approach even in the case that the phase steps are randomized and unknown a length evaluation is feasible. A possible drift of the length of the beam path can be considered for realizing the phase shifts depending on the speed of the drift. The latter could be compensated or supported by the built-in phase shifting components of the interferometer. Even in the presence of slight vibrations, which provoke a random step width, this approach can be used for the phase determination. The results of the measurements which are currently performed will be presented in a separate publication together with the details of the uncertainty analysis.

Acknowledgement

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References

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