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Homodyne full-field interferometer for measuring dynamic surface phenomena in microstructures

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ABSTRACT

We describe a stabilized homodyne full-field interferometer capable of measuring vertical surface deformations of microstructures in the time domain. The interferometer is stabilized to a chosen operation point by obtaining a feedback signal from a non-moving, freely selectable, reference region on the sample surface. The stabilized full-field interferometer enables detection of time-dependent changes in the surface profile with nanometer scale vertical resolution, while the temporal resolution of the measurement is ultimately limited by the refresh rate of the camera only. The lateral resolution of the surface deformation is determined by the combination of the imaging optics together with the pixel size of the camera. The setup is used to measure the deformation of an Aluminum nitride membrane as a function of time-dependent pressure change. The data analysis allows for unambiguous determination of surface deformations over multiple fringes of the interferogram, hence enabling the study of a wide range of physical phenomena with varying magnitude of vertical surface movement.

1. Introduction

The intense research and development of ever more sophisticated micro- and nanostructures and systems whose functionality is based on mechanical movements or deformations has evoked a need for advanced experimental methods to characterize their mechanical behavior. Electromechanical devices with vibrating microstructures, for example, are today key components in high-performance, miniaturized radio-frequency filters used in mobile communication systems [1–3].

Optical interferometry enables non-contact, direct characterization of surface vibrations even down to the sub-picometer amplitude levels for frequencies up to GHz range [4–8]. This has proven a successful combination in characterizing acoustic wave fields in electroacoustic components [9]. In addition to vibration measurements, there is also a need to detect movements in the time domain, including, e.g., transients, impulse responses, and repeatable or non-repeatable single events.

A measurement setup for versatile studies of surface movements in the time domain should generally have a good temporal resolution combined with a high spatial imaging resolution and it should not perturb the mechanical behavior of the sample under study. Furthermore, the technique should also allow for measurements over long time periods in order to enable studies of deformations with slow trends. Hence, potential drifts and fluctuations in the measurement system need to be carefully eliminated or compensated for. In case of microstructures, a lateral imaging resolution of about 1 μm is often desirable to correctly determine the dynamic behavior in complex structures whilst the area of interest may extend even up to millimeters. A high resolution and a wide dynamic range are required as in typical applications the surface movement may range from relatively large, micrometer-order deformations down to nanometer or even less.

Although various single-point and full-field interferometric setups and concepts have been developed for measuring surface dynamics in microstructures [6,7,10–20], many of those methods have been intended for measuring time-periodic surface vibrations only and are not applicable for detecting time-aperiodic surface deformations. Moreover, the combination of the aforementioned requirements for large-area, long-term measurements of even sub-nanometer surface movements in microstructures with ~1 μm lateral resolution and high temporal resolution constitutes a challenge for many of the existing techniques.

We have earlier demonstrated an active stabilization concept for full-field stroboscopic interferometry that enables imaging of surface vibration fields in microstructures with a minimum detectable amplitude limit of less than 30 pm [21]. In that work, the detection concept was developed for measuring vibration amplitudes of less than 100 nm to avoid ambiguities caused by the periodicity of the interferometric signal. Here we report a camera-based interferometer, which uses a similar stabilization approach to enable full-field measurement of out-of-plane surface

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movements of microstructures in the time domain. Furthermore, we present a data analysis method that allows for an unambiguous measurement of large surface deformations, where the height range may extend over multiple periods of the periodic interference signal. A prerequisite of this analysis is that the rate of change of the surface deformation is sufficiently small with respect to the camera frame rate such that the time-dependent interference signal can be recorded without ambiguity.

For stabilizing the interferometer to an operation point, a reference signal is obtained from the data extracted from a freely selectable reference region within the imaged area. Since each pixel is analyzed individually, the lateral imaging resolution of the deformation field is as good as the imaging resolution defined by the camera and the imaging optics. In this method, the temporal resolution of the surface deformation measurement is ultimately limited by the camera refresh rate only. To demonstrate the concept and the capabilities of the setup, we present a measurement of the surface deformation of an Aluminum nitride (AlN) membrane as a function of a time-dependent pressure difference applied across the membrane.

2. Detection principle and experimental setup

Our concept for measuring surface deformations in time domain enables a compact full-field interferometer design with flexibility in the choice of both the interferometer configuration as well as its optical components, see Fig. 1. The stabilization method only requires a software-selectable, non-moving surface region within the imaged area together with a means to control the optical pathlength in one of the arms of the interferometer. In fact, it is also possible to use a surface region with uniform and sufficiently slow movement as a reference.

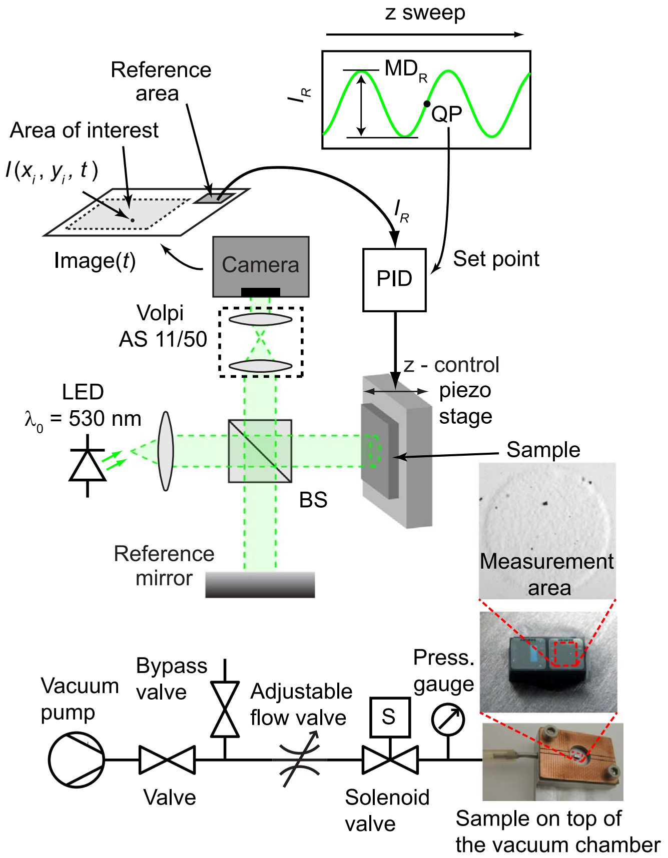

Fig. 1. Schematic presentation of the actively stabilized interferometer setup for the measurement of surface movements in time domain, together with the pressure control setup and the membrane sample used for the experimental measurement. In the measurement, a vacuum pump is used to create a time- dependent underpressure below the membrane.

For the illumination, a variety of light sources can be used, provided that their coherence length is long enough to result in an interferogram that extends over the height range of interest for the measurement. In our measurement example, typical for mechanical movements of microstructures, the height range of the measurement is less than few micrometers, and hence even a light-emitting diode (LED), with a relatively wide emission spectrum, provides an attractive combination that offers both a speckle-free illumination and a sufficient coherence length. As the detection is sensitive to fluctuations and drifts of the intensity of the light source, a highly stable DC illumination is required unless the intensity variations of the source are monitored and compensated for.

In our full-field Michelson interferometer setup schematically presented in Fig. 1, a green LED with a center wavelength of $\lambda_0 = 530$ nm and a spectral width of 30 nm (FWHM) is used for the illumination. The drive electronics of the LED has been carefully designed to provide a stable and low-noise DC light intensity.

The light is collected with an aspheric condenser lens to form a nearly collimated beam, which is split into the reference and sample arms of the interferometer by a non-polarizing beam splitter (BS) cube. The two light beams incident on the sample and on the reference mirror are then reflected back and recombined in the BS. The resulting interference pattern is recorded with a 12-bit monochrome camera (Point Gray BFLY-PGE-09S2M) equipped with long working distance video microscope optics (Volpi AS 11/50). This combination results in a camera pixel corresponding to 0.92 µm on the sample surface whereas the lateral imaging resolution is better than 4 µm, limited by the performance of the imaging optics. The sample is mounted onto a piezoelectric translation stage in order to allow for a control of the optical pathlength difference between the two arms by adjusting the *z*-position of the sample along the optical axis. Equally well, the pathlength difference could be controlled by moving the reference mirror.

The setup is built on an optical table with active vibration isolation (Newport i-2000) to eliminate high-frequency mechanical perturbations from the environment. The remaining mechanical noise arises from slow drift and fluctuations, which are compensated for by the active stabilization of the interferometer's pathlength difference.

For the stabilization, a software-based feedback loop controls the optical pathlength difference between the two arms of the interferometer such that the interference signal in a non-moving reference region on the sample surface stays at a constant intensity. To accomplish this, a mean intensity I_R over the pixels in the reference area is calculated and compared against a pre-determined set point, corresponding to, e.g., the quadrature point (QP) of the interference signal, where the interferometer has its highest sensitivity to small variations in the pathlength, see the inset in Fig. 1. The difference is used as an error signal in a software-based proportional-integral-derivative (PID) controller that actively controls the piezoelectric stage, and hence, the optical pathlength difference in the system.

The set point for the feedback loop is defined at the beginning of the measurement by recording I_R as a function of the *z*-position of the sample during a linear *z*-sweep of the piezoelectric translation stage. In the typical case of stabilizing the interferometer to a QP, the setpoint is found as a midpoint between the maximum and minimum value of the interference fringe having the highest modulation depth, $\mathrm{MD_R}$. In general, the set point is freely selectable between the maximum and minimum value of any fringe to