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Measuring vibrations in interferometric optical profilometry through imaging fringes at 1kHz

Chaoren Liu, Carlos Bermudez, Guillem Carles, Roger Artigas

Sensofar Tech, S.L., Parc Audiovisual de Catalunya, Ctra. BV-1274, KM 1, 08225 Terrassa (SPAIN)

cliu@sensofar.com

Abstract

Monitoring and controlling vibrations are critical not only for precision manufacturing, but also for high precision optical metrology. There are many sources of vibration that might influence the performance of a system: environmental acoustic noise, seismic vibration, resonances caused by the movement of internal motors, etc. The ability to measure and analyze such vibrations is crucial to evaluate the environment in which the system is installed. This includes the determination of the origin of the vibrations, the assessment of their impact on the performance of the system and, ultimately, the possibility to investigate possible solutions for their suppression. Optical profilometers employing high magnification microscope objectives may be severely affected by vibrations, which introduce jitter or blur in the acquired sequence of input images, depending on the frequency of the vibration. Since processing of such images is used to reconstruct the output topography, this has a serious detrimental effect on the quality of the three-dimensional surface measurements.

In this work, we present a method for obtaining the vibrational information of an interferometric optical profiler. It is based on the acquisition of a time sequence of the interference fringes at a sufficiently high frame rate to enable measurement of vibrations of up to 1 kHz. Because we use the camera of the profiler itself, no additional hardware is required. We demonstrate the approach by computing the vibrational response of a commercial optical profiler to input environmental acoustic noise, at a range of controlled frequencies. The method is readily applicable to any image-based interferometric system, enabling to determine its dynamics, and to use it as a proxy to monitor the surrounding environment. Additionally, it may be used to measure the anti-vibrational performance of isolating platforms which are common components in high-precision optical systems.

Keywords: acoustic, interferometry, metrology, vibration

1. Introduction

Microelectronics have undergone significant development in recent decades, leading to the attainment of sensors with heightened sensitivity and reduced response time. These advancements, coupled with rapidly evolving metrology techniques, have propelled us into the nanometer-scale era. The fabrication and characterization of materials at this scale is very demanding and the ability to monitor the processes and inspect components with high precision has become essential. Optical metrology offers non-invasive and high-performance methods for such tasks. However, the control of vibrations is crucial for high-precision inspection.

Vibrations can introduce jitter or blur to images, depending on the vibration frequency relative to the image sampling rate. Such effects significantly impact techniques such as interferometry. For example, in phase scanning interferometry, vibrations can introduce measurement errors [1]. As a consequence, the accuracy and the repeatability of the metrological system are affected by vibrations. Although the sensitivity to such errors appears to be algorithm-dependent, achieving complete immunity to vibrations remains challenging.

Numerous studies have investigated how vibrations impact metrology system performance, spanning processes related to data acquisition (optical and structural considerations) as well as algorithmic design [2–6]. On the other side, structural mechanical design of the instruments becomes crucial to minimise vibrations. For example, it is important to design the mechanics of the instrument such that the most problematic frequencies are attenuated. Therefore, a method to assess the impact of different sources of vibration directly from the metrological instrument is of great interest. Here, a method to precisely measure these vibrations in an interferometric optical profiler is proposed, by using a simple analysis of image profiles acquired at 1 kHz.

There are various sources of vibrations in manufacturing environments, such as seismic events, passing vehicles or personnel, acoustic noise from the environment, or vibrations induced from moving parts [7]. Controlling noise at a manufacturing site is challenging due to the difficulty in locating the sources and determining the response under such perturbation, especially when dealing with vibrations at the micrometre per second level. Additionally, internal movement within the system like scanning stages, can also introduce vibrations.

Optical tables are commonly employed to isolate vibrations. However, depending on the table's characteristics, some external vibrations may be transmitted, and even resonances may appear in extreme cases. Similar scenarios can occur in the support structures where metrology equipment is placed. For example, a passing staff member may induce vibrations with a frequency matching the pneumatic spring of the workbench [8]

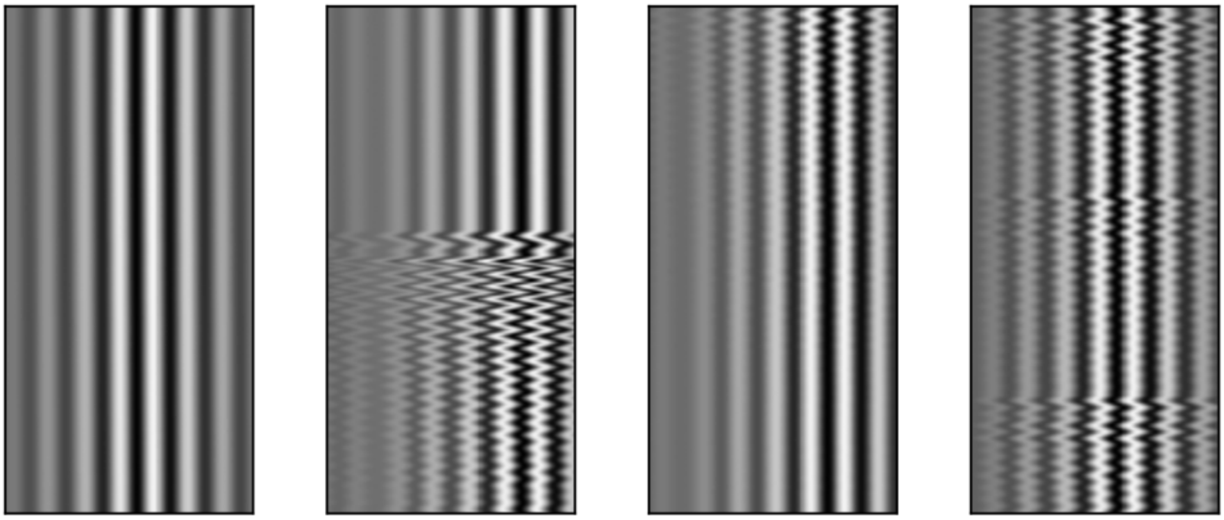

Figure 1. Example of sequence-images obtained from accumulating fringe profiles over time. The horizontal direction captures the fringes generated by the interferometer imaging a tilted mirror. The vertical direction captures the variation over time. The series correspond to a duration of 5 seconds. In the different examples, sporadic knocks on the table induce vibrations that are captured by the sequences, acquired at 1 kHz.

Addressing vibrations involves various strategies depending on the system's damping behaviour, including removing vibration sources, interrupting transmission routes, or altering system characteristics. From a structural designer's perspective, utilizing commercial products like optical tables or active anti-vibration tables, along with established solutions such as anti-vibration legs or constrained layer damping, proves beneficial. In cases where dominant frequency acoustic noise is unavoidable and an acoustic isolation cabinet cannot be installed, structural redesign becomes essential to shift the intrinsic resonance frequency away from identified perturbations.

In all, to mitigate the impact of vibrations, the first step is to identify their characteristics and assessing their impact on system performance. In this study, a straightforward yet efficient method to determine the influence of vibrations directly from the images acquired in an interferometric optical profiler is presented.

2. Methodology

A software module was developed to capture images from an interferometric optical profiler using a camera running at 1000 fps. To achieve such high speed, the stored region-of-interest in the camera was reduced to single-line images of 1 × 2448 pixels. The system uses a Mirau-type interferometric 10×/0.3NA objective. A flat mirror at the sample plane was placed tilted at an angle such that, in the direction of the acquired line-image, interferometric fringes appear. Time sequences of 5 seconds at 1 kHz sampling rate were captured, and so each sequence required to store 5000 time-sequence line profiles in memory. For convenience, such sequences were stored in 2448 × 5000 images, in which each row contains the captured fringes, and columns capture the variation in time. Example sequence-images are shown in Figure 1.

Note how vibrations are captured directly in this sequence-images because a variation in the axial distance causes a phase shift in the fringes. Such phase shift can be readily detected by measuring the relative horizontal shift in each line. This was done by Fourier transforming each line independently and extracting the phase of the main spatial frequency component, which is readily identified from its high magnitude in the Fourier transform. Finally, the phase of such Fourier component is related to the amplitude of the relative shift by a simple relation: a complete period of 2π radians corresponds to a distance of $\lambda/2$, where λ is the nominal wavelength of the light. In all, the amplitude of vibration over time is computed from each sequence-image, where the displacement:

$$z = \frac{\lambda * \psi}{4\pi} \tag{1}$$

where ψ is the phase of the fringes. Since calculation of displacement (used here to determine the amplitude of vibration) is determined by the physics of light interference, there is no calibration involved and accuracy is intrinsically very high. The main uncertainty for accuracy is the determination of the effective wavelength, which is of course set by the light source but also affected by the numerical aperture of the objective used. Besides this, other sources of error include: the error in identifying the fringe frequency associated with the sample tilt (which is arbitrary), and the error in determining the phase value of the frequency component from each noisy line-image. These sources of error are in practice zero-mean perturbations and affect only the precision of the measurements. We assessed their overall impact directly from measurements: we measured the instrument noise by acquiring sequences of unperturbed samples over time in an isolated environment, such that, variations could be associated only to measurement errors. Such instrument noise was measured to be below 1 nm.

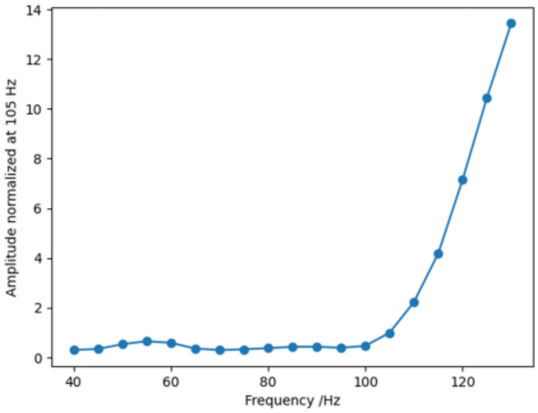

Figure 2. Response of the speaker at different frequencies, measured using a microphone.

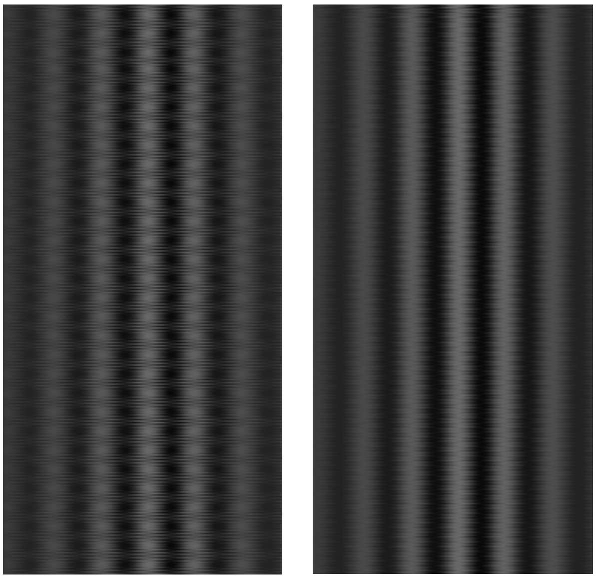

Figure 3. Sequence images obtained for input acoustic excitation at (left) 70 Hz and (right) 75 Hz, as example acquisitions.

For qualitative illustration, the response of the system to external knocks on the optical table was measured, and some examples are shown in Figure 1. It can be visually appreciated how knocking on the table causes a vibration, with particular dominant frequencies, that attenuate over time at a given rate.

Because the aim is to assess the impact of vibrations into the measurements, the time-frequency components of the extracted amplitude sequences were analysed, when the system is perturbated by acoustic input at various frequencies. To do this, the power spectral density (PSD) of the time series was calculated using the Welch method, for each stimulus. Experimentally, the perturbation was applied by playing a pure frequency sound on a 4 inch subwoofer speaker placed close to the optical profiler. Of course, the speaker does not have a constant spectral response, and to have an indication, the response of the speaker using a microphone (Rode, Lavalier) was measured, which is shown in Figure 2 for reference. The microphone has its own spectral response, but vendor specifications indicate that the variation is below 5 dB in the range of 40 Hz to 130 Hz [9].

3. Results

3.1 Vibration induced by knocking the optical table

As mentioned earlier, a qualitative assessment of the method by measuring the vibrations induced by sporadic knock on the optical table was performed. Results are shown in Figure 1, where the impact of vibrations and their attenuation over time is evident. This suggests that the system requires roughly 5 seconds to stabilize.

3.2 Vibration from induced vibration with controlled acoustic input

Here it is analysed how vibrations generated from acoustic input at different frequencies are transferred to the system. This includes how well each input is relatively attenuated and also how other resonant frequencies are excited, as a transmission matrix.

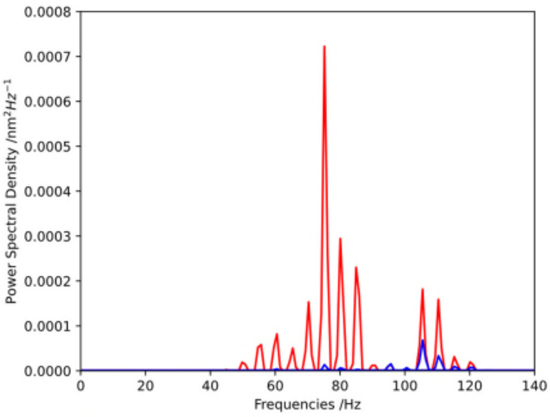

Figure 4. The calculated Power Spectral Density of the vibration amplitude induced in the interferometer is shown for the selected excitation frequencies. Blue and red representing with and without active anti vibration table respectively.

For each specified input frequency within the range of 40 to 130 Hz, a perturbation lasting 5 seconds was introduced, and the corresponding sequence-image was recorded. Examples of sequence images obtained with excitations at 70 Hz and 75 Hz are shown in Figure 3. The experiment was repeated in two different scenarios: with the system directly on an optical table, and with the system installed on an active anti-vibrational table.

Results are shown in Figure 4 and Figure 5, on a linear scale and in a form of a pseudo-coloured transmission matrix, respectively. In the case of pseudo coloured transmission matrix, each row of the matrix corresponds to a single pure acoustic frequency excitation, and the values shown across columns correspond to the impact generated at the images (following a PSD calculation). As expected, the matrix has a strong diagonal, but resonances appearing at harmonics of the excitation frequency also appear. Other intrinsic resonances should appear as vertical features, i.e. that are excited at any (or a range of) frequency. For example, small but detectable perturbations are noted at frequencies close to 30 Hz and 50 Hz.

Secondly, the results were repeated with the system installed on an anti-vibrational table. Active anti-vibrational tables play a crucial role where mitigating vibrations is imperative. In this study, the response of a system was assessed mounted on the Accurion® i4 table, as depicted in Figure 4. Lower PSD values are observed due to the effect of the anti-vibrational table. Results are shown in Figure 4. Similarly, we can observe the appearance of harmonics. Vibrations at 30 Hz and 50 Hz are now more attenuated, arguably through the anti-vibrational table, although the perturbation at 30 Hz is still noticeable, perhaps being associated to another intrinsic vibrational mode of the structure.

4. Conclusions

In this work, an effective method of quantifying the vibration was developed, based on the analysis of the time series of images obtained from Mirau type interferometric objective, with sampling rate of 1 kHz. The instrumental noise of the developed technique was calculated to be below 1 nm in our prototype. Using this method, the transmission matrix that characterises how external perturbations (in this case, in the form of acoustic excitation) are transferred and impact the system was measured.

Various methods are available for monitoring vibrations, with MEMS-based sensors being ideal if sufficient sensitivity is achieved. Other types, such as capacitor-based sensors

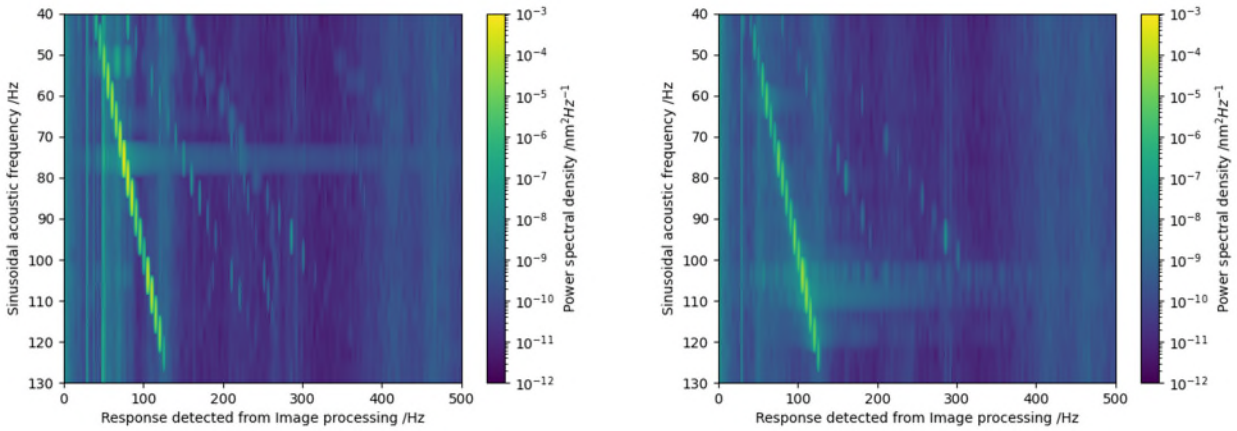

Figure 5. Power Spectral Density calculation of the vibration of the structure under forced vibration by acoustic disturbance for acoustic excitation at the selected frequencies, A false-coloured transmission matrix of the system is shown. (left) highlighting response of the structure, (right) in this case the instrument was installed on an active anti-vibration table.

employed in PIEZO, and external accelerometers with piezo functionality, are also valuable. However, the proposed method provides an alternative approach, efficient and easily implementable in the interferometers without necessitating additional hardware. Furthermore, the measurements are performed directly on the same camera that is used to operate the interferometer.

Using the developed tool, the impact of forced vibration induced by acoustic noise was observed. Notable effects included blurring and jagged fringes, with the resonance amplitude (response to acoustic noise) measuring around 50 nm. The dominant frequencies mirrored the disturbance frequency, exhibiting effects at double and triple frequencies.

The tool offers a straightforward means of determining the adequacy of ambient conditions for metrology measurements. It proves valuable for product development, providing a tool to assess anti-vibration performance effectively. The ease of implementation makes it a practical asset for evaluating the ambient environment's suitability for precise metrological measurements and contributes to the ongoing development of the optical equipment.

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