Vibration compensation platform for robot-based nanoscale measurements

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Abstract

Measuring properties at the nanometre scale such as topography, morphology and roughness within a production line becomes increasingly important for quality control and process monitoring tasks. In a production line, ground vibrations are transmitted to the sample and the inspection tool, corrupting nanoscale measurements by affecting the distance between inspection tool and sample. To enable nanometre scale measurements a mechanism is needed that keeps this distance constant. This paper describes the concept and experimental results of a metrology platform that tracks the sample for nanoscale inspection. The nano inspection tool is carried by the metrology platform and is artificially coupled to the movement of the sample by using a feedback controller. A one degree of freedom experimental setup was built for demonstrating tracking performance. The implemented closed loop control achieves disturbance rejection with a bandwidth of 410 Hz and reduces emulated on-site vibrations from ±500 nm down to ±9 nm, showing significant reduction of external vibrations.

Active vibration isolation, Nanometrology, Mechatronic system design, High precision measurement

1. Introduction

Ground vibrations in a production environment disturb measurements of nano inspection tools as they change the distance between inspection tool and a measurement sample. Commonly used methods that counteract ground vibrations use active or passive vibration isolation platforms supporting both, sample and inspection tool [1,2]. Such platforms lack flexibility and a smooth integration into a production line, as the samples needs to be taken out of the production line and be inserted again after inspection. In contrast, a different approach is to move the inspection tool along with the measurement table [3].

To maintain a constant distance between inspection tool and sample, this paper demonstrates an actively controlled metrology platform (MP) that tracks the sample at nanometre level. Fig. 1 shows the MP with a non-movable part interfacing a robot arm, and a movable part with the attached inspection tool, e.g. an atomic force microscope (AFM).

Tracking of the sample is achieved by the feedback controller that drives the tracking actuator based on the distance signal provided by the tracking sensor.

2. Experimental Setup

To demonstrate feasibility of tracking a vibrating sample, a laboratory setup was built as shown in Fig. 2. An aluminium body with a mass of 4.2 kg serves as mechanical structure of the MP suspended by a flexure mechanism for guidance [4]. To minimize the transmission of mechanical vibrations through the actuator, a Lorentz actuator is implemented as tracking actuator [5]. A flat sample is fixed to a loudspeaker setup that emulates on-site measured vibrations from a production line. The relative distance between the MP and the target is measured by a heterodyne interferometer (Agilent 10898A laser board) at a resolution of 1.25 nm.

For controller design, the dynamics of the MP from the force input $F_d$ to the position $x$ of the MP is approximated by a fourth order model in the Laplace domain as:

$$\frac{X(s)}{F_d(s)} = \frac{G}{s^2 + 2\xi_1\omega_1 s + \omega_1^2} \cdot \frac{1}{s^2 + 2\xi_2\omega_2 s + \omega_2^2}$$

(1)

With $G$ representing the gain and $\omega_1$, denoting the location of the first resonance caused by the suspension with the corresponding damping ratio $\xi_1$. The second term of Eq. (1) with $\omega_2$ and $\xi_2$ accounts for an internal mode shape of the MP represented by the decoupling mass $m_2$ in Fig. 1.

Initial system identification of the plant shows a first resonance appearing at $f_1 = \omega_1/2\pi = 9.8$ Hz and a second resonance appearing at $f_2 = \omega_2/2\pi = 3.2$ kHz. Fig. 3 depicts the measured plant $P(s)$ sampled at 20 kHz and the fitted plant model based on Eq. (1).
2.1. Controller Implementation

As controller serves a PD-controller with a tamed D-action to improve noise rejection at higher frequencies. To achieve a high bandwidth, additionally a Notch-Filter is used in series that compensates for the second resonance of the plant. The controller transfer function

\[
C(s) = \left( \frac{K_p}{1 + K_d s} \right) \frac{s^2 + 2 \omega_n s + \omega_n^2}{s^2 + 2 \omega_n s + \omega_n^2} \tag{2}
\]

With \(K_p\) as the proportional gain, \(K_d\) as the derivative gain and \(K_d\) as the parameter for taming the D-action. The notch filter is parametrized by the center frequency \(\omega_n = 2\pi f_c\), the depth \(\nu\) and the width \(\gamma\). \(K_d\) is used to raise \(P(s)\) to the desired unity-gain cross over frequency \(f_c\) of 750 Hz while \(K_d = 3K_p/2\pi f_c\) adds sufficient phase lead around \(f_c\) \([6]\). By using Tustin’s method, Eq. (2) is discretised and implemented on a dSPACE system (DS1005 platform) running at a sampling frequency of 20 kHz.

Figure 3. Bode plots showing the measured plant dynamics (plant meas.), the fitted plant (plant fitted) and the measured open loop transfer function (OL-TF).

3. Results

The measured open loop transfer function \(C(s) \cdot P(s)\) depicted in Fig. 3 shows a 0 dB crossing at 750 Hz, a phase margin of 27° and a gain margin of 5.8 dB. Due to the Notch-filter of the controller the second resonance has vanished. The sensitivity function depicted in Fig. 4 shows disturbance rejection below 410 Hz but amplification above this frequency due to Bode’s sensitivity integral \([6]\). Fig. 5 shows a vibration profile measured on a production site including shock impacts that is emulated by the shaker.

During the emulated shock, the residual tracking error is kept within ±120 nm to prevent damage of inspection tools. When no shocks occur in the vibration signal, the controller suppresses ±500 nm movements of the sample down to ±9 nm.

4. Conclusion

In a production environment vibrations corrupt measurements of nano inspection tools as they change the relative distance between the inspection tool and the sample. In this paper it is shown that an actively controlled metrology platform (MP) can track a sample within a few nanometres, thus enabling high precision measurements with a nano inspection tool in a production environment.

To implement nanometrology in a production environment using this MP concept, the next steps are mounting the MP in an upright position to access the sample from above and integrating an on-board sensor for measuring the relative distance, as well as extending this concept to six degrees of freedom \([5]\) to track the sample in all spatial directions.

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