

Accurate Measurement of Micro-Newton Scale Dynamic Forces

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Extended Abstract

This paper presents a comprehensive technique for accurate measurement of dynamic forces at micro-newton scale within a broad frequency range to advance nanoscience and nanotechnology. Nanotechnology has come a long way in the past few years, and is expected to continue to grow at a rapid rate [Horniyak et al. (2009)]. Nanometrology is a key enabling technology for both process and quality control to realize many advancements in nanoscience. For instance, nanometrology plays a crucial role to reproducibly create precise nano-scale features and parts in nanomanufacturing [Andrew et al. (2010)].

A critical challenge in nanometrology is to devise new measurement techniques that will meet the needs of nanotechnology applications. Recent advances in metrology instruments, such as interferometer, have enabled successful application of dimensional and surface metrology through non-contact displacement measurements in nano-scale [Andrew et al. (2010)]. However, some advanced techniques must yet be established for accurate force measurement in nanotechnology applications [Horniyak et al. (2009)]. In particular, although micro-scale static force measurement has been demonstrated in the literature [Horniyak et al. (2009). and Andrew et al. (2010).], the techniques for *in-situ* measurement of high-frequency dynamic forces at micro-newton level are still needed.

To address the aforementioned need, the commercial atomic force microscopy (AFM) beams, which are pre-calibrated using the thermal fluctuation technique [Levy et al. (2002).] for determining their static stiffness values, have hitherto been used [Puchner et al. (2009)]. Briefly, an AFM beam with a natural frequency of ω_n behaves like a simple stiffness element at relatively lower frequencies ($< 0.2*\omega_n$). This enables the measurement of dynamic forces imparted onto AFM beam up to $0.2*\omega_n$ by monitoring its deflections using a non-contact displacement sensor and using its static stiffness value. However, the downside of this method is the low stiffness of AFM beam, which leads to high deflections impeding the performance of the nanotechnology applications.

In this paper, we present a new microcantilever-based dynamic force-sensing approach for accurate measurement of micro-scale forces within a wide frequency range, while minimizing the deflections of the microcantilever to obviate the drawbacks of the AFM beams-based force measurement technique. To this end, first, a microcantilever is designed and fabricated to achieve micro-scale dynamic force measurements up to 20 kHz. Since the microcantilever is relatively larger for stiffness requirements, it has natural frequencies within the frequency range of interest. Hence, it should be dynamically calibrated instead of having a single static-stiffness value. For the dynamic calibration purpose within a 20 kHz bandwidth, a step-sine approach is followed using a pre-calibrated AFM beam with a natural frequency of 160 kHz. The AFM beam attached to a piezoelectric actuator is used to impart sinusoidal forces onto the microcantilever by stepping from one frequency to the next with a 10 Hz resolution. The measured deflections of the AFM beam are proportional to the applied dynamic forces through its pre-calibrated

static stiffness value. While the AFM beam is used to apply the dynamic input force to the closest possible point to the fixed-end of the microcantilever, the ensuing dynamic displacement is measured at the free-end of the microcantilever. As such, while the deflection of the microcantilever at the site of interest is kept less than 1 nm, the amplified displacement at the free-end can be accurately measured using current non-contact displacement sensors. As a result, the calibration procedure yields to a frequency-dependent complex-valued calibration function, $[CF(j\omega)] = [F(j\omega)]/[X(j\omega)]$, where $[F(j\omega)]$ is the applied dynamic force at the fixed-end and $[X(j\omega)]$ is the measured displacement at the free-end of the microcantilever. This calibration function is used to obtain accurate measurement of micro-scale dynamic forces during nanotechnology applications in which the displacement at the free-end of the microcantilever is monitored. The measured displacement data at the free-end is processed through previously obtained calibration function to convert them into dynamic force values. The conversion is executed in frequency domain for both magnitude and phase, and then the inverse fast Fourier transformation (iFFT) is performed on the processed data to obtain time-domain force measurements. To exemplify, the presented approach was demonstrated on mechanical nanomanufacturing, nanomilling process developed by Gozen et al. (2012) to obtain accurate broadband nanomilling forces with micro-newton level force magnitudes. The nanomilling was performed at the location close to the fixed-end of the microcantilever while simultaneously measuring the displacement at the free-end of the microcantilever. As such, the presented approach provides an effective means of accurate measurement of micro-scale dynamic forces with high-stiffness requirements. Although the technique is demonstrated in only one-direction on a mechanical nanomanufacturing application, it can be advanced for dynamic force measurements in multi-directions, and used for different nanotechnology applications, including nanorobotics and nanotribology.

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