USE OF RADIATION PRESSURE TO CALIBRATE SUB MICRO-NEWTON FORCES AND DAMPING RATIOS

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ABSTRACT

We present a noncontact method to calibrate micro/nanostructures using sub-nN forces. In this work, a microcantilever’s material properties as well as damping ratio are determined using two independent laser systems. A continuous wave laser system is used as a heterodyne interferometer to determine displacements while another laser system is pulsed in order to produce radiation pressure. A noncontact method is preferred while calibrating sub-μN forces since no material is transferred between the calibrating apparatus and (NEMS/MEMS) to be calibrated. The incidence force is calculated from the optical properties of Si cantilever. Simulations presented in this work shows that thermal gradient along the length of the cantilever beam is very small to affect its physical properties due to the difference in time scales on which both operate.

INTRODUCTION

Measurement of small forces (fN to nN) are the cause of numerous scientific breakthroughs in the last few decades. These measurements have been the subject of intensive research in different contexts such as molecular forces using optical traps [1], atomic force microscopy (AFM) [2], fundamental physics of micromechanical structures [3], etc. The vast majority of force measurements made below a μN are for the purpose of determining material properties. Examples are: measurement of single ligand-receptor interactions (~fN–pN) using the Surface Force Apparatus (SFA) [4-5], measurement of the mechanical properties of nanostructures (nN–mN) using Nano/Microelectromechanical Systems (NEMS/MEMS) [6-8], and a plethora of measurements have been made on the range of pN to nN using the Atomic Force Microscope (AFM). These measurements are becoming increasingly common, and thus calibration of the force response of these measurement systems in differing environments is extremely important.

An important consideration in NanoMetrology is the well-known “Observer Effect.” The gist of the Observer Effect is that by measuring a quantity of an object one has necessarily disturbed that objects state. At the macroscale this may be a negligible effect, e.g. attaching a thermocouple to the hull of a ship. The thermocouple is taking an insignificant amount of thermal energy away from the ship such that the measurement of the hull’s temperature has not changed by its measurement. At reduced size scales this may not be true. If a thermocouple is attached to an AFM tip, that has smaller dimensions than the thermocouple, then the cantilevers thermal state has been altered considerably. Much in the same way, contact between a force calibration device and a nanoscale object could very well change the volume of the object by either addition or subtraction of mass.

An exchange of mass occurs when parts contact; this exchange may be only atoms, but even this may change the properties of a nanomaterial or nanodevice. The method of calibration by the electrostatic force balance (EFB) and its artefacts are inherently contact methods. Thus caution should be exercised with these methods. Even if the contact method is amiable to calibration of the device considered, calibrations are still not possible below 10 nN [2, 9].

Because there is no traceable force standard at the sub-nN scales researchers have taken matters into their own hands.
Most researchers use a classical-theoretical approach to calibration by modeling their device as a linear elastic spring using:

\[ F = kx \]  

(1)

where \( F \) is the force, \( x \) is the displacement and \( k \) is the spring constant. The basic approach is to measure the displacement for a known load and extract a device 'stiffness'. This device stiffness, \( k \), is typically a function of the elastic modulus and the geometry of the device. Yet, it is well known that these parameters are common sources of variation in flexible micromachined mechanisms [10]. Furthermore, many researchers assume that the device geometry is well-defined. Typically the device cross-section is assumed to be rectangular even though it is common knowledge that most fabrication processes involve etching steps that are notoriously asymmetric and introduce a measurable degree of taper that produces trapezoidal cross sections [8]. An additional concern is the variation of material properties. For example, the elastic modulus of Si can vary more than 100 GPa depending on the extent to which the Si was doped and what dopant was used [11].

The following details our preliminary work using a pulsed laser system in order to determine static and dynamic properties of a microcantilever beam. Dynamic calibration of microcantilevers are of great importance because of their use in many applications, the most prominent of which being AFM measurements. Herein we determine the material properties of a cantilever beam as well as its damping ratio at STP conditions.

**EXPERIMENTAL SETUP**

The experimental setup is composed of five components: a source of radiation force, micro-cantilever beam, displacement measurement system, high precision linear stages and two microscopes. New Wave Research’s Quicklaze 50 STII system with Green laser (532 nm) is used as a source for the radiation pressure. The laser is mounted on a microscope and fixed horizontally on a vibration isolation table. The laser system is a pulsed laser with Q-switching that is capable of delivering known amounts of energy in 4ns pulses. By mounting the laser on the microscope this energy pulse can be focused on to a very small spot.

Separately, Polytec’s single point laser doppler vibrometer (LDV) head with microscope is mounted on a system of precision linear stages and fixed on the opposite side of the vibration table. LDV uses 1 mW red laser (633 nm) to determine the position by heterodyne interferometry. LDV makes use of heterodyne interferometry to detect both velocity and displacement of a moving object. A heterodyne interferometer compares two separate light waves/signals; one signal is the light scattered by the moving object and the second is a reference signal generated by the LDV. Velocity is determined by detecting changes in the frequency of the incoming light. The displacement of the moving object, though, is determined by looking at the phase modulation of the incoming light signal [12]. The output from the LDV is a continuous analog voltage that is proportional to the target displacement along the direction of the laser beam.

Finally, a silicon micro-cantilever beam (1500 µm long, 30 µm wide and 2.6 µm thick) is fabricated using SUMMiT V microfabrication technique and mounted on a separate set of precision linear stages to facilitate its alignment between the two microscope objectives. The complete experimental setup is shown in Figure 1.

![Figure 1: Experimental setup](image1)

The two laser systems are focused on the opposite sides of the micro-cantilever beam (Figure 2). Since the two laser systems used have different wavelengths therefore the chances of force laser (green, 532nm) affecting the measurements of LDV (red, 633 nm) are minimal. But the stray light from the powerful force laser can potentially damage the detection system on the LDV for this reason the two laser beams are focused 150µm apart on the cantilever beam (Figure 3).

![Figure 2: Microcantilever beam is shown positioned between the two microscope objectives](image2)
EXPERIMENT

An 8 µJ pulsed laser was focused and fired at the tip of a 1500 µm long Si cantilever beam. With the pulse duration of the beam of 4 ns, the power of the laser beam imparting the momentum (radiation pressure) to the cantilever is therefore 2 kW. Radiation pressure exerted on an object moving with a velocity \( \nu \) (relative to the light source) can be calculated using incident radiation power, the reflectivity (R) and the absorptivity (A) of the object:

\[
F_{\text{rad}} = \left( \frac{2RP_{\text{in}}}{c} + \frac{AP_{\text{in}}}{c} \right) \left( 1 - \frac{\nu}{c} \right)
\]

Note that Equation 2 contains terms for the reflected portion of the incident beam and also the absorbed portion. A photon reflected off of a surface imparts twice the momentum of an absorbed photon. Therefore the term with a factor of 2 is the reflected portion and the term without 2 is the absorbed portion. Additionally, note that \( \nu/c \sim 0 \) because the relative velocity of the cantilever is always \( \ll c \).

RESULTS AND DISCUSSION

Mechanical Response

The displacement response of the cantilever beam is shown in Figure 5. The maximum displacement on the first oscillation is 57 nm.

From the damped frequency (\( \omega_d \)) and damping ratio (\( \zeta \)) values the natural frequency of the system can be calculated from equation (3).

\[
\zeta = \frac{c \zeta}{\omega_d} = \sqrt{1 - \left( \frac{\omega_d}{\omega_n} \right)^2}
\]
This natural frequency of the system is used to calculate the Young’s Modulus of 129 GPa. Natural frequency and damping ratio are calculated (equation 4 [13]) and are given on Table 1.

\[ \omega_n = \frac{\beta_n l}{\sqrt{\frac{E l}{\rho A l^4}}} \]  

(4)

It can be seen from Table 1 that the higher modes of oscillations for the beam are critically damped and only 1st mode oscillations are under damped:

<table>
<thead>
<tr>
<th>Mode</th>
<th>( \beta_n l ) [13]</th>
<th>( \omega_n )(Hz)</th>
<th>Damping ratio (( \zeta ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.875104</td>
<td>1487.118</td>
<td>0.041</td>
</tr>
<tr>
<td>2</td>
<td>4.694091</td>
<td>9319.611</td>
<td>0.987</td>
</tr>
<tr>
<td>3</td>
<td>7.854757</td>
<td>26095.178</td>
<td>0.998</td>
</tr>
<tr>
<td>4</td>
<td>10.9955441</td>
<td>51136.172</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Table 1: Calculated values of natural frequencies and damping ratios for various modes of vibration

Thermal Response Simulations

To study the thermal effects of the incident laser on the microcantilever a transient thermal analysis was performed using finite element method. In this analysis, the beam was modeled using two dimensional thermal elements. Each element comprises of four in-plane nodes, and the ambient temperature was applied to the nodes located on the fixed side of the cantilever. The laser spot on the tip of the beam was modeled using uniform heat generation equal to the laser power. Discretization of this model was performed in ANSYS. The silicon’s thermal conductivity and specific heat are taken to be 150 W/mK and 700 J/kgK, respectively. In this simulation, first the heat generation is applied to the elements inside the laser spot for 4 ns, then the heat generation is removed and the transient response of the system is recorded until 1 ms. For time integration, the Newmark method is employed with a number of time steps and a mesh fine enough to ensure the convergence of the solution. The transient thermal response of the beam to the laser pulse is depicted in Figure 7.

![Figure 7: The transient thermal response of the beam to the laser pulse](image)

Here, the temperature is plotted for two distinct points, one on the center of the laser spot (Point A) and the other on the tip of the beam (Point B). Since Point A is located on the center of the laser spot and the point B is on the side furthest from the heat sink, anytime the maximum temperature of the beam can be observed on one of these locations. As expected, overall maximum temperature of the beam occurs at the end of laser pulse and on the center of the laser spot. This peak is boxed and dubbed with number of 1 on the plot.

The temperature contours of Peak 1 are illustrated in Figure 8. As shown, even though the maximum temperature is 2056 K, only a very small region on the tip of the beam experiences this high temperature and the probable change of material properties will only minimally affect the stiffness and natural frequency of the beam. Note that 2056 K exceeds the melting temperature of Si (1687 K), but not the boiling temperature (3538 K). The authors acknowledge that the material properties of Si change with changing temperature; however in this preliminary work this effect is neglected. Although the temperature does exceed the melting temperature of Si this only happens in a small localized area and for on the order of 10 ns. It is expected that restructuring of the Si may have occurred in this area. In fact, the physical appearance of the Si changes slight under the laser spot’s landing area, however consistent results are obtained under subsequent pulses indicating a minimal effect.
Figure 8: The temperature contours of the laser spots at various times taken from Figure 7.

The insignificance of thermal effects on the mechanical behavior of the beam becomes more evident as Peak 2 (Figure 7 and contour 2 on Figure 8) also shows a very small high temperature area on the tip of the beam. Box 3 (Figure 7) shows the time associated with the end of the first mechanical oscillation period. At this time, the overall temperature difference on the beam is less than 80 K which minimally affects the material properties. In essence the thermal analysis shows that the high temperature regions occur on small areas on the tip of the beam and at a period of time smaller than mechanical oscillation period. Accordingly, the thermal effects of the laser excitation on the mechanical properties can be neglected in calculation of mechanical properties. This is supported by the constant period between free oscillations of the beam in the experiment, see Figures 5 and 6. Had the beam been cooling while oscillating the period of the oscillations would have been changing, i.e. the period would have varied in Figure 5 and the mode at 1487 Hz in Figure 6 would have been wider or displayed multiple peaks.

CONCLUSION

There is need for calibrating micro/nanostructures using sub-μN forces. The preceding article described a noncontact dynamic method for determination of the material properties of a microcantilever and damping ratio in varying environments. This method utilized a pulsed laser system with a pulse duration on the order of nanoseconds. It was shown that this pulsed can be considered an impulse with respect to the mechanical system. Additionally, it was determined that although the structure underwent a temperature increase that the thermal effects dissipated before the mechanical system was able to respond to the impulse thereby not compromising the measurements.

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REFERENCES