USE OF PHOTON PRESSURE IN SMALL MASS AND FORCE CALIBRATION

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The recent redefinition of the International System of Units (SI) provides opportunities to improve scaling in mass and force metrology. The use of photon pressure force to improve metrology in the nanonewton to piconewton range has the potential to overcome difficulties encountered in developing traceability for this range of forces. Several experiments conducted to compare photon pressure force calibration to other existing methods demonstrate the feasibility of this approach to small mass and force calibration.

INTRODUCTION

Mass and force calibration are typically carried out using calibrated weights. This approach becomes problematic moving to mass below about 100 micrograms (force less than 1 micronewton.) The difficulty in handling the small calibration weights and the uncertainty in their mass values increases the smaller the weights become. The use of a photon pressure force is one way to circumvent these problems, as it provides a reference force in a direction defined by the reflecting surface that is traceable to the SI via laser power calibration methods. Several experiments have been carried out to examine the validity of this approach

EXPERIMENTS

The NIST Electrostatic Force Balance (EFB) has been used to measure photon pressure force at the nanonewton level. The EFB is an electromechanical balance system that uses traceable measurements of capacitance, displacement and voltage to provide a primary reference for mass and force [1]. By attaching high-reflectivity distributed Bragg reflector (DBR) mirrors to the top and bottom of the EFB, and alternately reflecting a laser from these mirrors, a differential force is generated while minimizing thermal drift [2]. A second measurement used a parallel-mirror etalon to increase the photon pressure force, and data is shown in Fig. 1. The single- and multiple-reflection force measurements were consistent with each other, but both differed from the photon pressure force predicted from an in-situ measurement of laser power by approximately 5 %. The operating conditions of the reference laser power detector used for the in-situ measurement may have contributed to the difference, since the detector was calibrated in air but used in vacuum during the EFB comparison. By using the optical switch in pulsed mode, the force could be continuously varied with high linearity by varying pulse duty cycle.

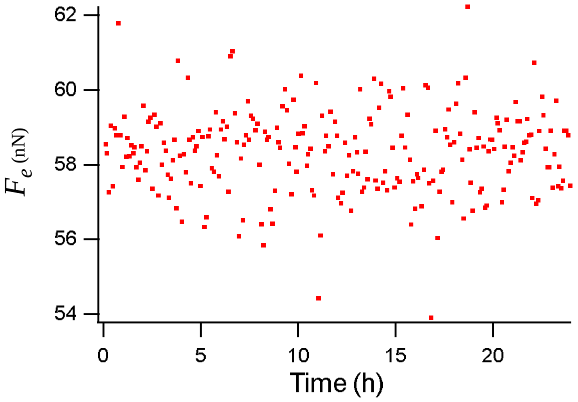

Figure 1. EFB force measurement in multiple reflection configuration.

Force below 1 nanonewton has been measured using chip-scale optomechanical systems. The mechanical sensors are millimeter-scale fused silica parallelogram flexures. Integrated optical fibers provide both a means to apply the photon pressure force, and an interferometer to read out the resulting displacement. When low-finesse fiber optical cavities are used, femtonewton resolution can be obtained with a maximum force of approximately 100 pN [3]. A cross-check of the mechanical flexure stiffness using a calibrated mass shows sub-percent agreement with the photon pressure force predicted by measuring the power of the laser used to drive the optomechanical system. The use of higher-finesse optical cavities allows for a larger maximum force of several nanonewtons, due to the buildup of circulating optical power within the cavity. The displacement response at the sensor's mechanical resonance frequency is shown in Fig. 2. In this case, the maximum photon pressure force is several nanonewtons. The accuracy of the reference force provided by measuring the optical power delivered to the sensor is heavily dependent on the modelling of the optical properties of the cavity, however [4]. The properties of the sensor itself are very stable, with the laser power force calibration varying less than 2 % over approximately two years of testing. This indicates these types of devices are useful as transfer artifacts.

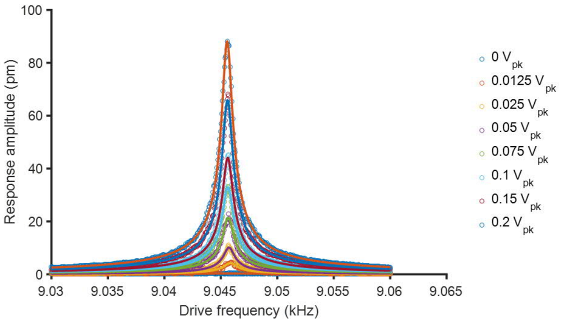

Figure 2. Displacement response to modulated photon pressure force on a flexure sensor from a high-finesse fiber optic cavity. Legend shows uncalibrated modulation amplitude for laser.

Table 1. Calibration strategies for different force ranges.

Force Range	Sensor Type	Reference
300 µN – 1 nN	EFB	[2]
10 nN – 10 pN	Flexure, resonant optical cavity	[4]
50 pN – 10 fN	Flexure, low finesse cavity	[3]

CONCLUSION

A suite of techniques is available that allows the use of photon pressure to provide force references that are traceable to the SI. Different techniques are appropriate for different force ranges and accuracy requirements. The use of photon pressure forces is potentially useful for a wide variety of small force calibrations, such as those used in atomic force microscopy (AFM,) gravitational wave detectors, instrumented indentation, and particulate mass measurement.

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