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Optical measurement of microscopic forces and torques

T. A. Nieminen, N. R. Heckenberg, and H. Rubinsztein-Dunlop,

Centre for Laser Science, Physics Department,
The University of Queensland, Brisbane QLD 4072, Australia.
tel: +61-7-3365-3405, fax: +61-7-3365-1242, e-mail: timo@physics.uq.edu.au

Abstract

Many spectacular successes have resulted from the use of laser trapped particles as force-sensing probes. For example, the forces applied to a DNA molecule as an RNA copy is made have been measured [1], as well as the physical properties of DNA [2, 3]. Optically trapped particles can be used to probe small forces and weak interactions which cannot be readily measured in any other way due to extreme sensitivity to ambient conditions [4].
A number of groups have made measurements of trapping forces [5, 6, 7], with differing levels of sensitivity and accuracy. However, a serious and fundamental problem common to virtually all measurements of this type is the lack of reliable absolute measurement. Viscous drag forces are generally used for calibration, which immediately presents the problem of changes in viscosity resulting from heating by the trapping beam. Since the optical trapping forces are due to the transfer of momentum from the beam to the particle, it is in principle possible to measure the applied force and torque by measuring the momentum of the scattered light. Direct optical determination of the force and torque gives an absolute measurement, immediately eliminating difficulties with calibration.
The theory of direct optical measurement of forces and torques acting on laser trapped non-spherical and birefringent probe particles is presented.

1 Introduction

The use of laser trapped particles as force-sensing probes allows the study of small forces and weak interactions with minimal disturbance of the ambient conditions. For example, forces acting on organelles within living cells, intermolecular forces (eg forces applied to a DNA molecule as an RNA copy is made [1]), and forces acting within colloids [4] can all be studied.

However, such measurements are limited by the lack of reliable absolute calibration. For example, measurements of optical force from comparison against viscous drag or from oscillation frequency spectra [5, 6] present problems due to changes in viscosity resulting from heating and the effect of nearby surfaces and particles on the viscous drag.

An optical trap is based on the attraction of small particles to regions of high intensity in a tightly focussed laser beam. This gradient force (and other forces due to absorption, reflection, etc - termed scattering forces) results from the transfer of momentum from the trapping beam to the particle. Optical torques will result if there is a transfer of angular momentum. Since the optical forces and torques result from the change in momentum and angular momentum of the beam, it is in principle possible to measure the applied force and torque by measuring the momentum of the scattered light. Direct optical determination of the force and torque gives an absolute measurement, immediately eliminating difficulties with calibration.

2 Optical force measurement

To measure the optical force and torque acting on a particle, we must measure the momentum and angular momentum carried by the incident trapping beam and the scattered field. We note that the momentum of an EM field is

$$\mathbf{P} = \epsilon_0 \int \mathbf{E} \times \mathbf{B} d^3x \tag{1}$$

and the angular momentum is

$$\mathbf{L} = \epsilon_0 \int \mathbf{x} \times (\mathbf{E} \times \mathbf{B})\, d^3x. \tag{2}$$

The momentum flux is proportional to, and in the same direction as the energy flow $\mathbf{S}$ ($= \mathbf{E} \times \mathbf{H}$). Noting that all of the light passes through a small volume of a few microns cubed at the focus of the trap, the direction of propagation of the scattered light field at some distance from the trap will simply depend on the direction from the trap centre. Thus, a detector can be used to measure the intensity of the scattered light as a function of position.

Some serious difficulties, however, remain:

- It is generally impossible to collect all of the scattered light. To collect more than the forward scattered light emergent from the bottom of the trap will be very difficult.
- The bottom of the trap (usually a microscope slide) will reflect some of the scattered light, and will change the direction of the scattered light.
- Reduction of error due to the scattered light not coming from a single point requires the detector to be a relatively large distance from the trap centre. The size of the detector will limit the distance at which the detector can be placed and still collect all significant forward-scattered light.
- The finite spatial resolution of the detector limits accuracy.

The actual accuracy attainable with a given detector is therefore of interest. The accuracy will depend on the total area covered by the detector, its spatial resolution, and intensity resolution, range, and sensitivity.

A simple, and practical, detector to use is a CCD array placed beneath the microscope slide forming the bottom of the trapping cell. The CCD array should be as large in area as possible, with as many pixels as possible, and should be placed as far away from the trap centre as possible while still collecting all significant forward-scattered light (see Fig. 1).

If the trap and particle are well-described theoretically, the scattered field can be predicted for all positions and orientations of the particle. Therefore, measurement of the scattered field can be used to determine the position and orientation of the particle [7]. In this way, the optical force and

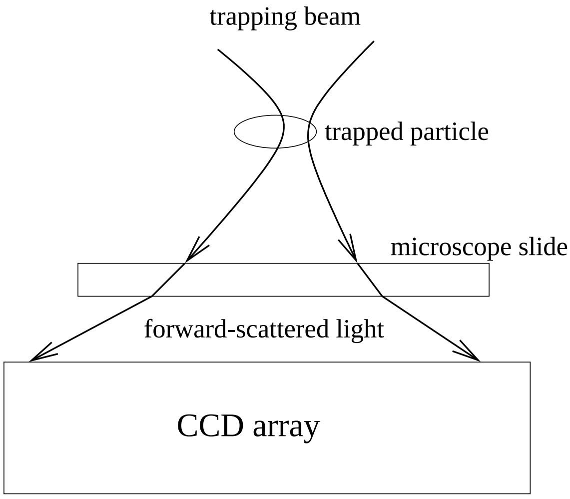

Figure 1: CCD array placed to detect forward-scattered light.

particle position can be simultaneously measured, and, for example, elastic properties of biological membranes could be measured by a suitable probe particle.

Knowledge of the expected scattered field can also allow determination of the entire scattered field through measurement of only a very small portion of the scattered light, for example by a number of photodiodes.

3 Optical torque measurement

Recognising that most of both the incident and scattered light propagates approximately along the beam axis, we can write the angular momentum of the beam in terms of a polarisation:

$$L_z = c\sigma_z P/\omega. \tag{3}$$

where L_z is the angular momentum about the beam axis and σ_z is the degree of circular polarisation, with $\sigma_z = \pm 1$ for purely circularly polarised light, and $\sigma_z = 0$ for plane-polarised light. The torque about the beam axis is then a function of the incident and scattered polarisations:

$$\tau = (\sigma_{zin} - \sigma_{zout})\, P/\omega. \tag{4}$$

Two cases are of particular interest. Firstly, a birefringent particle will have a uniform angle-independent torque acting on it when trapped by a circularly polarised beam [8]. Secondly, non-spherical particles, and birefringent particles, will align in a particular orientation when trapped by a plane-polarised beam. If the particle can freely move to this orientation, there will be no torque acting. If, however, the particle cannot move freely, there will be an optical torque acting on the particle, which can be used to measure the restraining forces.

The polarisation of the scattered beam can be measured by measuring the intensity through a plane-polariser, which will result in a sinusoidal variation of the intensity as the particle rotates [9, 10]. This will provide simultaneous measurements of the optical torque and the rotation speed of the particle. The torque acting on a stationary particle can be measured by rotating the plane-polariser through which the intensity is measured.

In general, the typical construction of an optical trap will make the measurement of torques other than that about the beam axis very difficult.

4 Conclusion

Optical measurement of the optical force and torque acting on a particle in a trap eliminates calibration difficulties by giving a direct measurement of the force. In addition, the method is equally applicable to moving particles, and stationary particles, and can therefore be used where methods such as measuring rotation rate or viscous drag required to escape the trap cannot be used at all.

The force acting on an unknown particle can be measured, so particles naturally occuring within, say, living biological specimens can be used as probes. Alternately, a known probe particle can be used to simultaneously measure the force and position, allowing investigation of the elastic properties of a wide variety of structures and macromolecules.

The elimination of the dependence of torque measurements on viscosity also allows the study of unknown fluids, to measure, for example, unknown viscosities, visco-elastic properties, or the effects of nearby walls or particles on viscous drag.

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