Measurement of optical trapping forces on irregular samples and complex beams with T-series force sensors by *IMPETUX*

Introduction

As optical trapping evolves, the use of non-spherical samples or non-Gaussian beams is becoming routine. The use of complex synthesized microparticles, the simultaneous manipulation of multiple samples with holographic optical tweezers or the measurement of forces on cells or subcellular structures inside them are just some examples. The large quantity of applications where traditional force calibrations fail to capture the physics of the laser-sample interaction motivates the expansion of new developments to deal with this increasing complexity.

With the exception of some simple cases, the prediction of forces on general samples and with general intensity distributions can be only achieved through complex computer simulations. The linearization of the force as a method to determine this magnitude from the displacements of the trapped object is essentially restricted to synthetic glass or latex microspheres. Thus, the measurement of forces on irregular samples with arbitrary traps opens the technology to a wide range of new possibilities.

T-series by *Impetux*

The measurement of forces is typically achieved by virtue of the linear relation between the applied force and the displacement of the sample in the trap [1]. This restrictive condition limits the use of optical trapping to well-controlled experiments.

Impetux offers a new product line of force sensors (Fig. 1) that uses a patented technology [2] to overcome the existing limitations. Our technology uses the deflection of the laser beam as a direct measurement of the force, without the requirement of an *in situ* calibration and therefore with no restrictions upon the properties of the sample. For further information, see Refs. 3 and 4.

Fig. 1. Force sensors *Lunam*™ T-40i and *Deimus*™ T-10i by *Impetux*.

Results

To show the possibilities that *Impetux*'s technology offers, optical forces were measured on isolated glass cylinders (Nippon Electric Glass, PF-50S). Lengths of the sample, L, varied between 20 and 40 μm, whereas the radius, a, was constant (2.5 μm). To hold these large cylinders parallel to the chamber surfaces, it was not possible to use a single trap so we stabilized the particles grabbing each cylinder by its two ends with two holographic traps (Fig. 2a).

Using a constant flow, we applied hydrodynamic forces of controlled magnitude on the trapped rods. Forces measured with the *Lunam*™ T-40i, F, were used to determine the drag coefficient by means of the Stokes law and compared to the theoretical values given by [5]:

$$\begin{aligned}\gamma_{\parallel} &= \frac{F_{\parallel}}{v} = \frac{2\pi\eta L}{\ln\left(\frac{L}{a}\right)+\ln 2-\frac{3}{2}-\frac{3L}{16h}}\\ \gamma_{\perp} &= \frac{F_{\perp}}{v} = \frac{4\pi\eta L}{\ln\left(\frac{L}{a}\right)+\ln 2-\frac{1}{2}-\frac{3L}{8h}}\end{aligned} \qquad (1)$$

where, η is the water viscosity, v the fluid velocity and h the trapping height. The last term, dependent on the ratio L/h, accounts for the effect of the vicinity of the chamber walls.

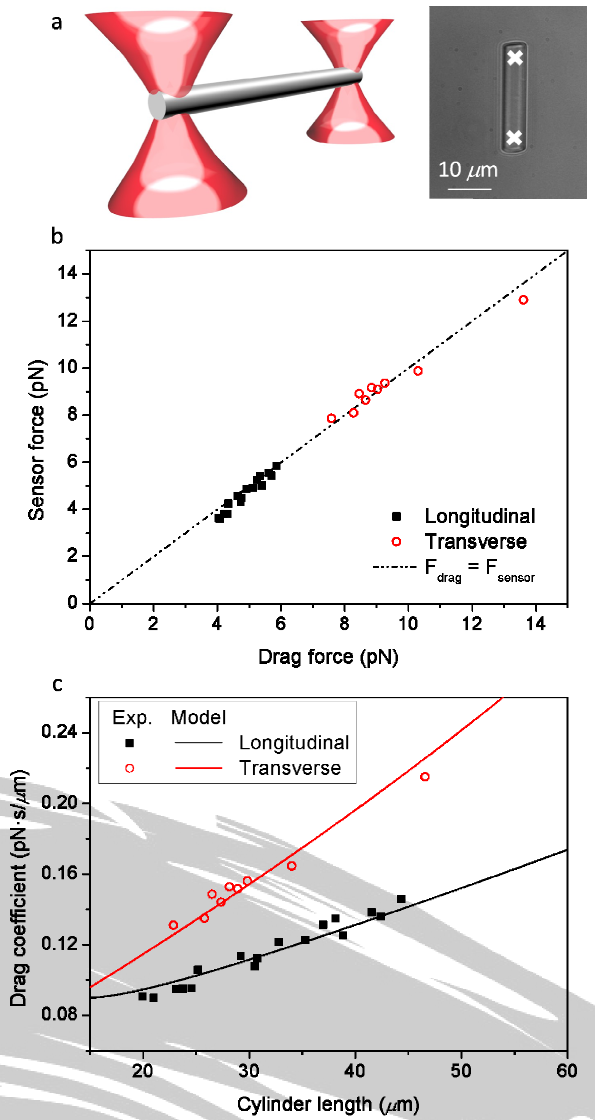

Fig. 2. Experimental force measurements on glass cylinders with two holographic traps.

The experiment was repeated with 25 different cylinders. Discrepancies between measured and theoretical forces were smaller than 5-10% (Fig. 2b), within the errors associated to the determination of the cylinder lengths, obtained from video image analyses.

The drag coefficient measured in the experiment as the ratio of the output force and the fluid velocity followed the predicted model [5] for the two perpendicular directions of the force (Fig. 2c). A determination of the exact radius of the cylinders followed from the fitting to the experimental data. The outcome for the longitudinal and transverse directions, 2.36 ± 0.03 μm and 2.53 ± 0.07 μm, was in good agreement with the nominal value (1% and 6%, respectively).

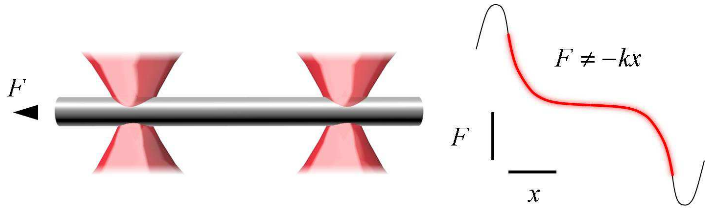

Fig. 3. Typical force curve for a cylinder with a plateau of zero force at the center.

The compatibility of the theoretical drag force and the sensor output for both longitudinal and transverse motions indicates that measurements were correct despite of using non-spherical samples with two holographic traps and that, therefore, force and particle displacements did not keep a linear relation (Fig. 3).

Applications

The power of measuring forces on more general situations other than those offered by traditional systems with microspheres and single Gaussian traps, has tremendous implications in different fields. The study of microswimmers, the determination of hydrodynamic properties of complex microstructures, the manipulation of large specimens from multiples points, the analysis of collective properties of colloids or the validation of computer simulations are some of the applications that will clearly benefit from the technology of the T-series range of force sensors developed by *Impetux*.

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Further readings

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2. M. Montes-Usategui and A. Farré, *US Patent* 8,637,803 (2014).
3. A. Farré and M. Montes-Usategui, *Opt. Express* 18, 11955-11968 (2010).
4. A. Farré, F. Marsà and M. Montes-Usategui, *Opt. Express* 20, 12270-12291 (2012).
5. C. Brennen and H. Winet, *Annu. Rev. Fluid Mech.* 9, 339-398 (1997).