Optical tweezers with controlled force profiles

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Abstract: Optical trapping is an increasingly important technique for controlling the structure of matter that has mainly applications in biophysics and medicine. This article finds the way to maximaze the linear region of the radial force profile in Optical tweezers. We take attention on simulations, where it can be controlled the force profile and see how configurations of two and three very close traps affect to particles. Then the simulation results are compared with experimental force profiles of 1.87μm polystyrene beads to determine if truly the linear region has been elongated.

I. INTRODUCTION

Since the early 1970s, when Arthur Ashkin pioneered the field, the laser-based optical trapping has progressed a lot and nowadays optical traps continue to find applications in many fields of science such as physics, biology or medicine.

An optical trap is formed by focusing a laser beam with an objective lens of high numerical aperture. A force will be experienced by a dielectric particle near the focus due to the transfer of momentum from the scattering of incident photons. This force has normally been decomposed into a scattering force and a gradient force. While the scattering force pushes the particle in the direction of light propagation the gradient force pulls the particle towards the focal region. Thus, for stable trapping, the scattering force must be less than the axial component of the gradient force.

While the axial force might be useful for a broader approach on the matter, in this study attention is being centered around the radial force or "optical tweezer", as it has come to be known.

The force can be thought as a restoring force since it returns the particle to the equilibrium position, which it is near to the beam focus. This restoring force acts like Hooke's spring, Eq.(1) –where $\vec{F}$ is the force, α the restoring constant and $\vec{X}$ the displacement–, where its stiffness is proportional to the beam intensity. Therefore, for small radial shifts, the force applied to the particle can be easily calculated as it goes proportional to displacement.

$$\vec{F} = -\alpha\vec{X} \tag{1}$$

The traditional methods[1] for measuring forces in optical traps are based on the linear assumption. In other words, they rely on the linearity of the force with displacement. Nevertheless, they are not applicable to displacements away from focal point, where the trap stiffness changes.

Apart from these methods, we have the direct measurement of force, which is based in the measurement of the momentum transfer to the bead using a position sensitive detector. Despite of having the direct force measure, when it is necessary determining the associated displacement to it we make use of Hooke's law again to calculate it.

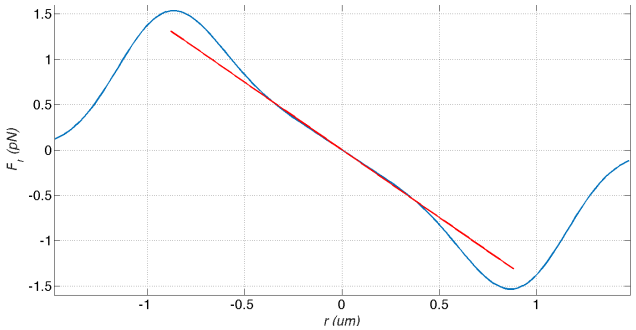

FIG. 1: Typical force profile of a single trap, in blue. The linear region of the trap, in red, has been extended to highlight the slope change close to r=-0.4 μm and r=0.4 μm.

The aim of this study is to minimize the change in the radial force profile [see Fig.(1)] so as to maximize the linear region of the force profile and so amplify the validity region of measuring forces with the mentioned methods.

II. TOOLBOX AND SIMULATIONS

To accomplish our purpose I ran several simulations in which I tested different combinations of overlapping traps. I used a toolbox implemented in Matlab for the computational modelling of optical tweezers. The toolbox is designed for the calculation of optical forces and torques and can be used for both spherical and non-spherical particles, in both Gaussian and other beams. The *Optical Tweezers toolbox 1.3* can be found at,

`http://www.physics.uq.edu.au/people/nieminen/software.html`

The toolbox is based in the complex Lorenz-Mie theory and the T-matrix method[2].

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A. One trap

For a better comprehension of the toolbox I started with a single gaussian beam. I studied how the profile shape changes with the radius and the refractive index of the particle. Other parameters, such as the beam waist, might also affect the simulation results but I did not consider them for our study since they produce little changes in the profile shape.

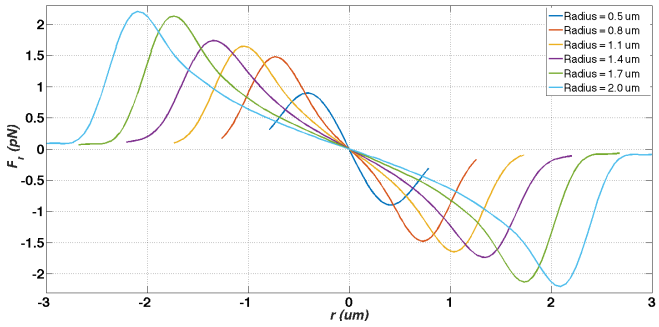


FIG. 2: Radial force profiles of a single trap for different bead sizes. The bead index refraction is 1.57 for polystyrene and 1.35 for the aqueous medium where the particle stays.

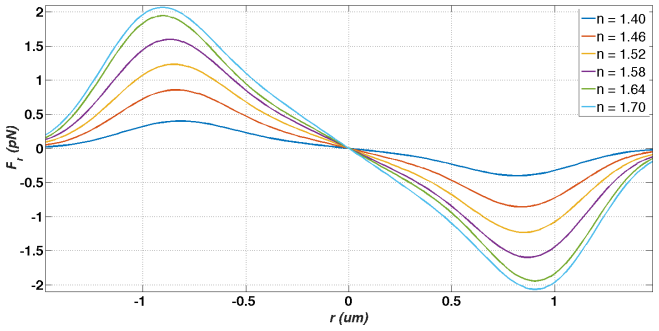


FIG. 3: Radial force profiles of a single trap for beads with different index refraction. The bead diameter is 1.87μm.

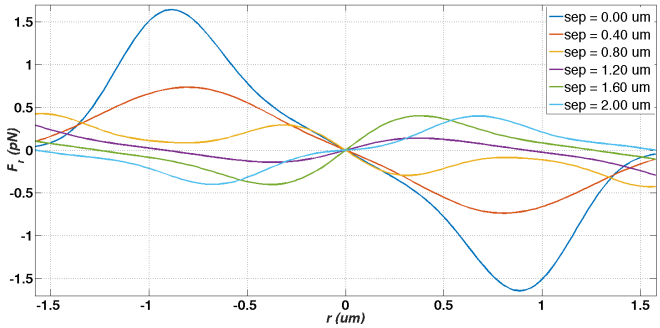
The particle size determines the profile length and the maximum force exerted by the optical tweezer, whereas a change in the bead index refraction only affects the force amplitude.

Having observed the dependence of the force profile with this variables, and considering that the experimental part is done with polystyrene particles of n = 1.57 and $\phi = 1.87\mu$m, next sections assume these values for the simulations.

B. Two traps

Using the toolbox and following the indications from the manual[3], I overlaid two traps leaving two parameters free: the distance to bead center of both traps and their relative phase shift. Afterwards, I created a simple code in Matlab that maximizes the linear region of the profile iterating in a distance range to the bead center of 0–1μm and in a range of 0–π for the relative phase shift.

For determining the linear region, the code evaluates if each profile point differs less than a 10% of the slope profile near the origin, where Hooke's law rules.



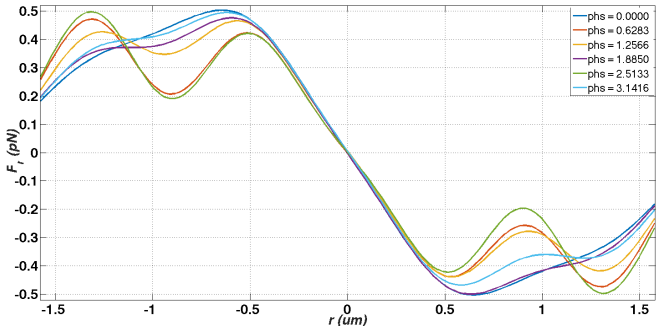


FIG. 4: On top, radial force profiles of a pair of traps where separation between them changes. The relative phase shift is null and one can see how the force amplitude decreases as separation between traps increases. Down, the figure shows how the relative phase shift affects the force profile. Relative phase shift between traps makes transition from peak to peak smoother. Notice the differences between e.g. phs = 0 and phs = 2.5133 in the range from ± 1.5 to ± 0.5 μm.

The simulation indicates that for spatially opposite traps distanced $\sim 0.4333\mu$m from the bead center and with zero relative phase shift, the linear region of the profile should be maximum, and it actually is. In fact, it practically makes all the profile linear from peak to peak, which leads to a significant increase of the linear region, enlarging it from $\sim 0.8080\mu$m to $\sim 1.4306\mu$m [see Fig.(5)].

The purpose of this study has already been reached with this kind of traps configurations. Nevertheless, the overlapping of three traps can give better results.

C. Three traps

The way to proceed in the simulations with three traps does not differ much from the two traps case. Briefly ex-

plained: two traps that are at opposite distances from the particle center, just like before, and an extra third trap fixed in the very middle of the bead. In order to generate a symmetric profile, the same relative phase shift is to be considered for both moving traps. Again, the iteration between a separation range of 0–1μm and between a phase shift range of 0–π is required to maximize the linear region of this configuration.

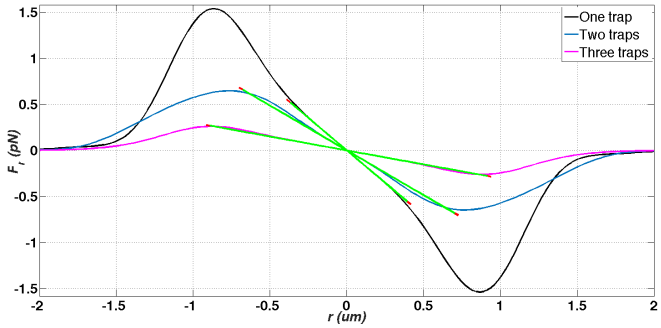


FIG. 5: Comparison of the three profiles. In black the single trap case, in blue the two traps configuration and in magenta the three traps configuration. The distance to the center for each traps is $\sim$0.4333μm for the double trap configuration while it is $\sim$0.1932μm for the triple trap configuration. For both configurations relative phase shift is zero. Red line highlights the linear region with 10% margin and the green line with a 5% margin with respect to simulated profile.

This time, for the optimization, the values of the parameters are $\sim$0.1932μm for distance between traps and zero relative phase shift. The linear region is now $\sim$1.8535μm, which represents an increase of almost a 130% with respect to the single trap. Certainly, this one is the best of both configurations, as it implies the greatest gain in the linear region.

Increasingly linearity involves a force loss as seen in Fig.(5). However, this only occurs when the total power of the configuration is maintained constant. If what we want is to have the force amplitude of a single trap in the three traps configuration, a power increase is needed. This would modify the slope of the linear region but not its length, since it just affects the force and not the profile distance from peak to peak.

III. EXPERIMENTAL

The key parts of the experimental set-up are: a TE2000 Nikon microscope, a 1064nm laser, a piezoelectric stage, which will allow the trap displacement through the bead, a holographic modulator[1, 4] that will create the configuration of traps when needed, and finally the Lunam^{TM} T-40i, which is going to do the direct measurement of force[5] through all the experiments.

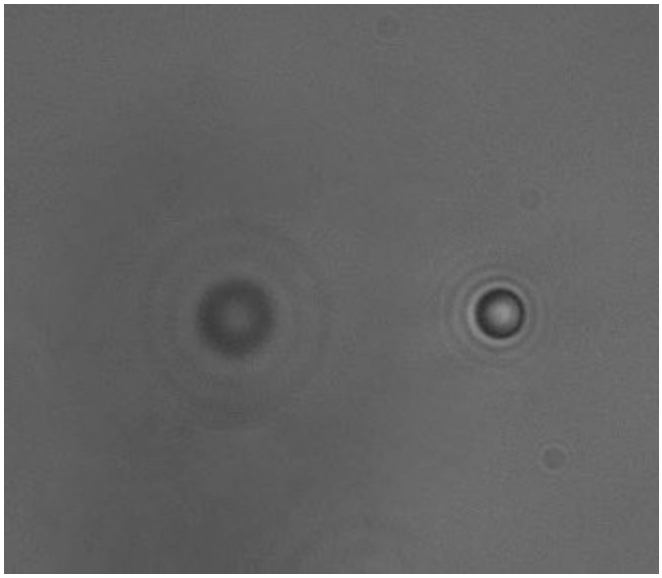


FIG. 6: Two polystyrene particles of 1.87μm. On the left, a bead out of focus attached to the glass slide. On the right, one trapped bead.

The beam does not allow to measure the force profile since once it traps a free polystyrene bead, this last one will follow every beam movement due to the stable trapping condition. Therefore, the samples with polystyrene particles must be prepared as follows:

- Firstly, a dissolution with a good particle concentration is put onto the glass slide as it is normally done.
- Secondly, the sample is dried so that the beads get attached to the slide.
- Finally, the sample must be rehydrated with the same dissolution.

These samples contain both, fixed and free particles. Free ones will help to determine, by imaging comparison, if the trap in fixed particles is focused at the correct axial distance –equilibrium axial point[1]. Thus, procuring equal conditions for both fixed and free beads.

Having focalized the beam into a fixed particle and radially centered it in the middle of the bead, the piezoelectric moves the sample in a specific direction that is controlled by a software implemented in LabVIEW. Therefore, the Lunam can characterize the radial force profile thanks to the particle movement, which allows the trap to cross from side to side of the bead.

Measuring with the Lunam, another manner that I used to corroborate that the trap was focused at the equilibrium axial point was to check its profile. If the trap is focused very close to the equilibrium point, the force profile will be similar to Fig.(1). Otherwise, it will lose amplitude and it would look more like a sinusoidal function.

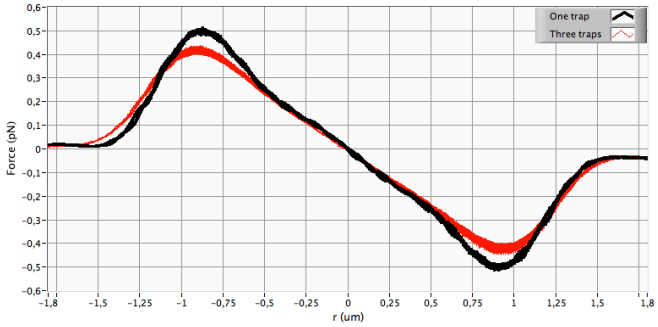


FIG. 7: Comparison of two experimental force profiles of a polystyrene bead: single trap configuration, in black, and three traps configuration in red.

For a specific configuration, the holographic modulator will create and will place the traps at the required distances with the relative phase shift needed. In the triple case, it divides the laser beam into three traps, one at the origin and the other two placed at $\pm 0.1932\mu$m with a null general phase shift. As it was expected, a gain with respect to the single trap configuration is obtained [see Fig.(7].

IV. CONCLUSIONS

From this paper we can draw that there is a way to control the force profile in optical traps. Particularly, I can say that in polystyrene beads of 1.87μm it is possible to enlarge the linear region of the radial force profile from $\sim 0.8080\mu$m to $\sim 1.8535\mu$m –since simulations strongly match with the experimental results [see Fig.(8)]–, making it virtually as if the radial force was proportional to displacement through all the particle size.

The obtained results strongly match with the computed ones. Showing that these results can be obtained for the rest of configurations would be an interesting subject for further research. In addition, due to the workload it would represent, research has only been done with fixed particles instead of free ones. Thus, it would be key to check if a identical outcome is obtained by using free beads.

Generating configurations of multiple traps is easy with the used toolbox, but the reason why the analysis stops at triple trap configurations is due to the fact that increasing the number of traps takes so much time as each free variable highly increases the iteration time in simulations. Despite of this, during simulation hours I found certain interesting configurations in which weak force clamp regions were intuitively deduced and where there was room for improvement by means of adding more traps.

To conclude, I encourage those who are interested in the field to go a step forward. For instance, I truly think that with this toolbox one can consider the creation of an algorithm responsible for the generation of force profiles with specific desired shapes.

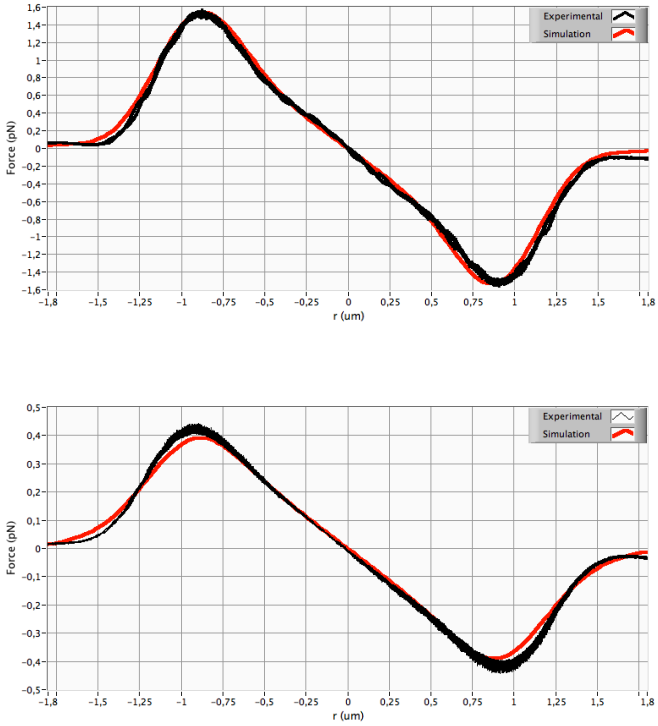


FIG. 8: Comparison of the experimental and simulated force profiles for the single trap configuration, on top, and for the triple trap configuration, down.

Acknowledgments

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Plus, I would like to acknowledge the support provided by my partner, family and friends during the preparation of this final year project.

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