An easier way to improvement the trapping performance of optical tweezers by donut-shaped beam

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ABSTRACT

In optical tweezers, it can be comprehended that the larger the inclination angle between the condensed laser beam and the optical axis contributes more to axial trapping force, while the central part of laser beam with smaller inclination angle contributes more transverse trapping force. Therefore donut-shaped beam is used to improve the problem of less-axial trapping for common optical tweezers. Some research reports have shown that the efficiency of a trapping force can be enhanced by using a donut-shaped beam. In this paper we present the dependence of the axial and the transverse components of a trapping force on the configuration of a focused donut-shaped beam. The simulation result will provide a simple and easy guide for optical tweezers users to adjust the configuration of a focused donut-shaped beam for optimal trapping performance.

Keywords: optical tweezers, donut-shaped beam, spring constant

1. INTRODUCTION

Optical tweezers, invented by Ashkin in 1986, are famous for their capabilities of trapping and manipulating a single particle by using a focused laser beam[1]. Because of non-invasive and non-mechanical, optical tweezers have been widely used in cellular and molecular biology experiments. However, the trapping force of optical tweezers is not radially symmetrical to the single trapping point, which may cause inconvenience in cell manipulation and biological force measurement. Therefore, it is beneficial for optical tweezers users to easily manage at will the distribution of a trapping force axially and transversely.

When a single particle is trapped in the focal point of laser beam, the trapping force can be separated into two force, gradient force and scattering force. The gradient force makes the particle toward the focal point and the scattering force pushes the particle away. It is essential for trapping the particle stably that gradient force must be more than the scattering force. However, a lot of intensity of the Gauss laser is in central part contributes more scattering force than gradient force on the particle. Improving the stable trapping force by removing the intensity of central part has been widely studied on laser trapping research[2]. Sato *et al.* increased the strength of a trapping force by 20% by using a cylindrical $TEM^{*}_{0,1}$ mode laser beam, in which the central part of the laser beam is much dimmer than the outer part of the beam[3]. Friese *et al.* raised a trapping force twice stronger by using a hollow laser beam consisting of helix wave front[4]. Yin and O'Neil *et al.* further raised the efficiency of a trapping force by using a doughnut or Laguerre-Gaussian mode laser beam, which is hollow[5,6].

In this paper, we present the dependence of the axial and the transverse components of a trapping force on the configuration of a focused donut-shaped beam. Specifically, we simulate the spring constants of the two components of the trapping force as a function of the inclination angle and the thickness, which means the difference of the outer and inner radius of the donut, of the focused donut-shaped beam with respect to the optical axis of an optical tweezers system, separately. The simulation result will provide a simple and easy guide for optical tweezers users to adjust the configuration of a focused donut-shaped beam for optimal trapping performance in cell manipulation and biological force measurement

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2. METHODS

In the ray-optics regime, the total laser beam is decomposed into individual rays, each with appropriate intensity and direction. Each ray must be followed Fresnel formulas. All calculation details are introduced[7]. Therefore, we compute scattering force F_s and gradient force F_g of each ray. Scattering force F_s and gradient force F_g are expressed as below:

$$F_s = \frac{n_1 P}{c}\{1 + R\cos 2\theta - \frac{T^2[\cos(2\theta - 2r)] + R\cos 2\theta}{1 + R^2 + 2R\cos 2r}\} \tag{1}$$

$$F_g = \frac{n_1 P}{c}\{R\sin 2\theta - \frac{T^2[\sin(2\theta - 2r)] + R\sin 2\theta}{1 + R^2 + 2R\cos 2r}\}\ , \tag{2}$$

and n_1 means the refraction index of surroundings, P is the power of incident laser beam and c represents the speed of lights. The R and T are the Fresnel reflection and transmission coefficients of the surface at the incident angle θ. Then project these tow force onto y and z axis which are described in Fig. 1:

$$F_{z(axial)} = -F_g \sin\varphi + F_s \cos\varphi \tag{3}$$

$$F_{y(transvese)} = -F_g \cos\varphi - F_s \sin\varphi \tag{4}$$

In this simulation, the total power P is fixed on 100mw under difference configurations of donut-shaped beam. Then, the axial trapping force F_z and transverse trapping force F_y respectively are calculated. In other specification, the particle is immersed in the water, the size of particle is 6 um in diameter and the refraction index of particle is 1.57. The numerical aperture of objective lens is 1.28 which means the maximum inclination angle, the angle between optical axis and incident direction, is 74.24° just like described in FIG. 1.

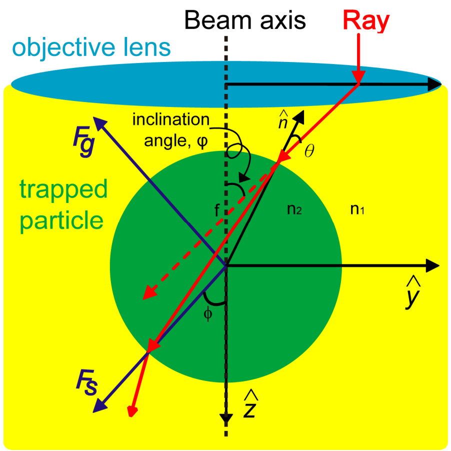

Figure 1. Geometry of an incident ray giving rise to gradient and scattering force contributions F_g and F_s

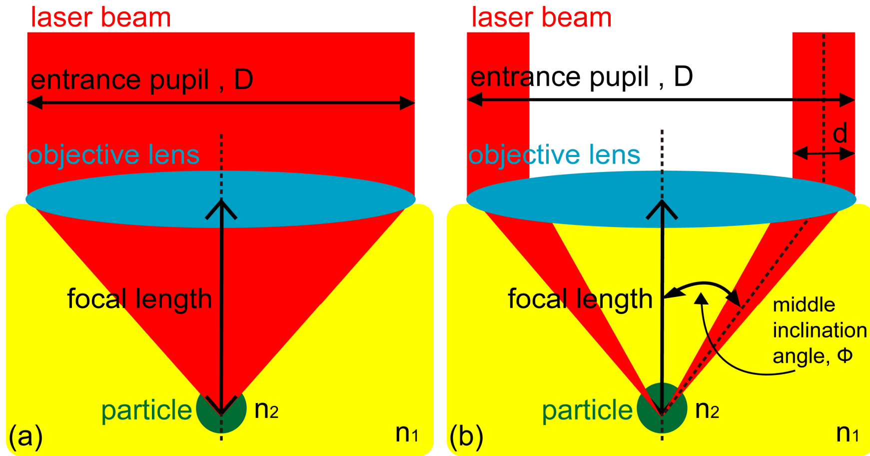

Figure 2. The sketches of (a) is the full beam commonly used in optical tweezers. (b) is the donut-shaped beam of optical tweezers we will mainly discuss in this paper.

In this paper, we simulate the forms of donut-shaped beam by modifying the middle inclination angle Φ and thickness d just like described in FIG. 2(b). The range of inclination Φ is from the optical axis to the maximum inclination angle φ. Thickness d is the percentage of the total entrance pupil diameter D. we calculate the axial trapping force F_z and transverse trapping force F_y respectively as the functions of inclination angle Φ and thickness d.

In laser trapping experiment, the trapping force for the particle is proportional to the distance between the position of particle and the focal point of objective lens. It behaves as a mass-spring oscillator with spring constant κ. So spring constant κ can represent the strength of the trapping force. Here the spring constant κ is defined as the slope of linear area in the illustration which describes in FIG. 3. We choose points A and B at –r/2 and r/2 as the end points to calculate the spring constant of optical tweezers. The r is the radius of the particle.

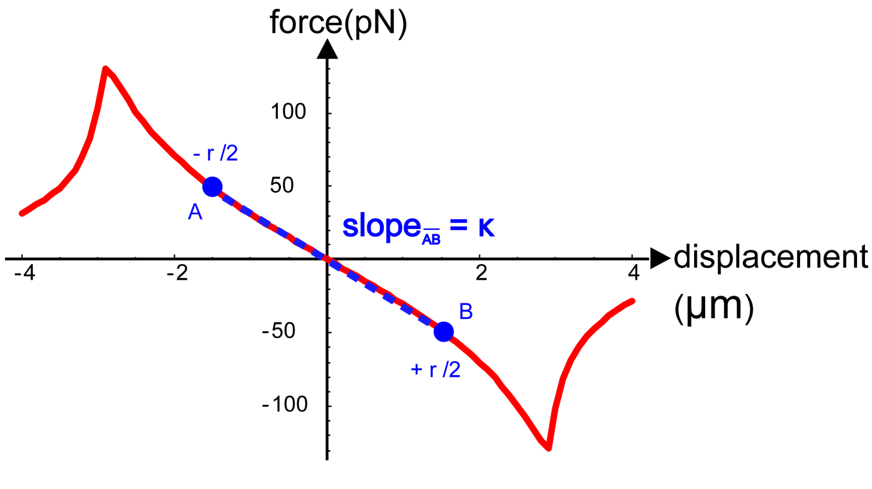

Figure 3. The transverse axis is the displacement from the trapped particle to the focal point and the vertical axis is the trapping force which is the particle receives. We choose points A and B as the end points to define the slope which is the spring constant of optical tweezers.

3. RESULTS AND DISCUSSIONS

In order to discuss the dependence of the axial and the transverse components of a trapping force on the configuration of a focused donut-shaped beam, the k_z and k_y are calculated as the functions of the d and Φ respectively.

First, we interest in k_z and k_y changing with d when the angle Φ is fixed and the results are shown as in FIG. 4 and FIG. 5. All of the spring constant values are normalized by k_0. In FIG. 4, the angle Φ is 65°, the variation of k_z/k_{zo} is only 1.0411% and one of k_y/k_{y0} is 1.037%. In FIG. 5, the angle Φ is 45°, the variation of k_z/k_{zo} is only 5.755% and one of k_y/k_{y0} is 1.86%. From two simulation results, all of variations are smaller than 10% and the trapping efficiency has weak dependence of the thickness d of donut-shaped beam.

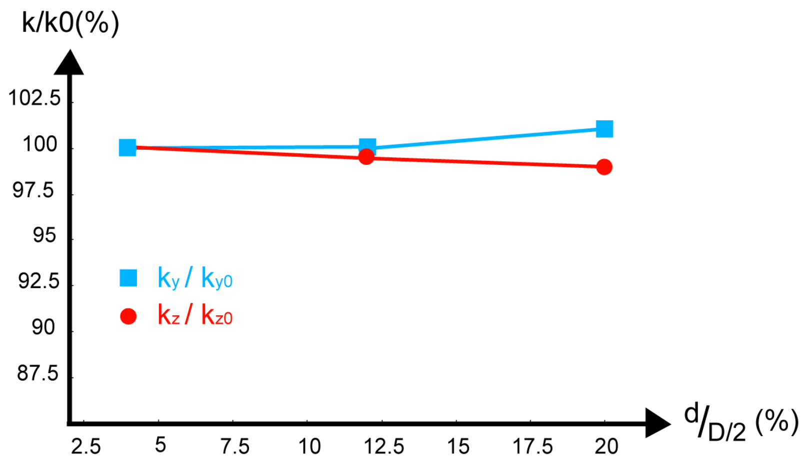

Figure 4. The middle inclination angle is 65° in this case. All of spring constant values are normalized by k_0 and expressed in percentage. The variations of k_z/k_{zo} and k_y/k_{y0} are smaller than 2% when the thickness d of donut-shaped beam change from 4% to 20% of half entrance pupil.

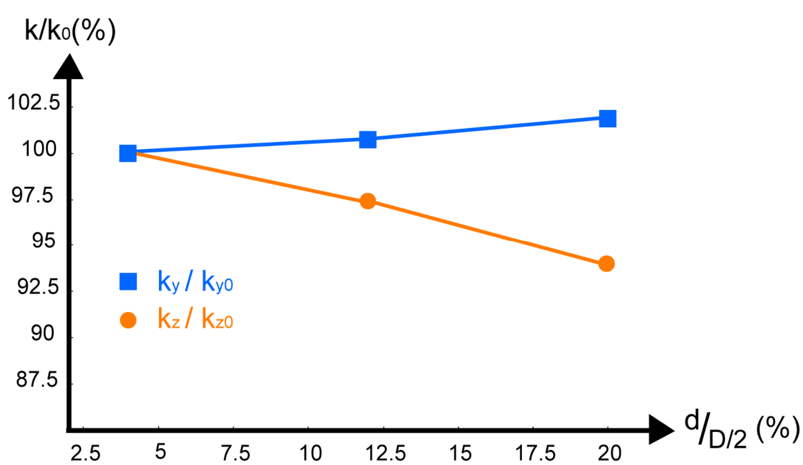

Figure 5. The middle inclination angle is 45° in this case. The variations of k_z/k_{zo} and k_y/k_{y0} are smaller than 6% when the thickness d of donut-shaped beam change from 4% to 20% of half entrance pupil.

Second, we interest in the trapping force efficiency in axial and transverse direction changing with Φ. Therefore, we calculate the spring constant κ_y and κ_z in axial and transverse direction respectively to represent the trapping efficiency. For a normal laser distribution like FIG. 2(a), the laser beam is the full beam and the spring constant κ_{y0} and κ_{z0} are calculated as 32.54 pN/μm and 29.75 pN/μm under our simulation conditions. To check how Φ effects trapping forces, we simulate different forms of donut-shaped beams by changing the middle inclination angle Φ, which varies from 0 to 74.24° and d is 2%D. In FIG. 7, all values of spring constants κ_y and κ_z are respectively normalized by κ_{y0} and κ_{z0}. When Φ closes to Φ_{max}, κ_z increases but κ_y decreases. However, the rising rate of κ_z is 0.74 (%/Φ), and the falling rate of κ_y is 0.30 (%/Φ). The total trapping force increases obviously while the middle inclination angle Φ increases. Therefore, the total trapping force ($\sqrt{F_y^2 + F_z^2}$) still increases with the increase of Φ because the increasing rate of F_z is faster than the decreasing rate of F_y.

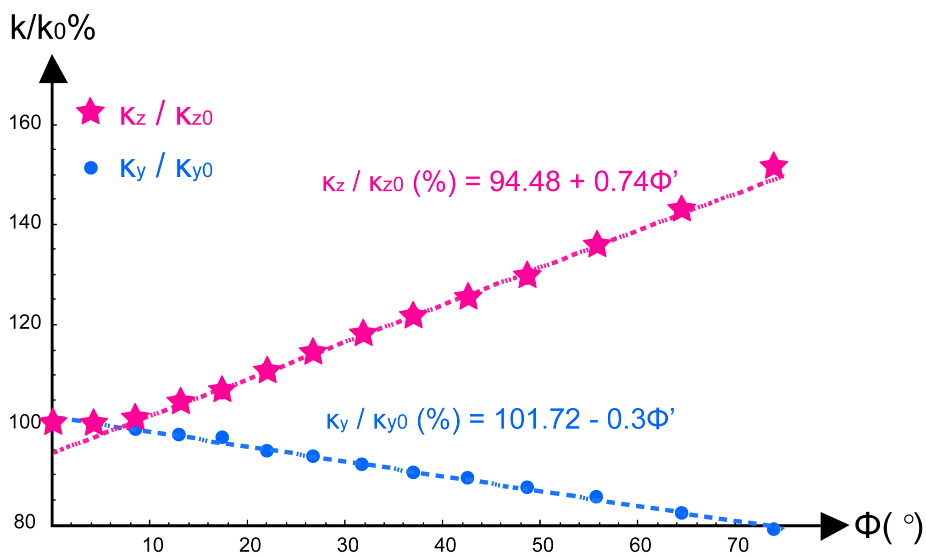

Figure 7. The angle Φ of donut-shaped beam varies from 0 to 74.24° and d is 2%D. All of the values of spring constant κ_y and κ_z are respectively normalized by κ_{y0} and κ_{z0}, which are the spring constants of normal optical tweezers described in FIG. 2(a). The rising of κ_z and the falling rate of κ_y are calculated by linear fitting method.

4. CONCLUSIONS

Donut-shaped beams are widely used to improve the trapping efficiency of optical tweezers. In this paper, we present a theoretical analysis about donut-shaped beams affect the trapping efficiency and conclude these with three important properties. First, as the inclination angle raising the spring constants k_z increase and spring constants k_y decreases. Second, the increasing rate of lateral spring constant is almost two times than the decreasing rate of transverse one. This means that donut-shaped beams can increase the total trapping efficiency. Third, compared with inclination angle, the thickness of the donut-shaped beam does less effect on the trapping efficiency. This simulation result will provide a simple and easy guide for optical tweezers users to adjust the configuration of a focused donut-shaped beam for optimal trapping performance in cell manipulation and biological force measurement

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