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INCREASING TRANSVERSE STABILITY OF OPTICAL TWEEZERS BY USING DUAL-GAUSSIAN BEAM PROFILE*

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Trapping force was calculated with a homogeneous dielectric sphere model. Results indicate that the transverse trapping force of optical tweezers can be increased effectively through modifying laser beam profile while the axial stability of the system is still assured. This is quite important when optical tweezers are applied to the precise measurements for single biological molecule.

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I. INTRODUCTION

Over the past 20 years, optical tweezers have been used to manipulate micro and submicro dielectric particles. In addition, calibrated optical tweezers can be used to measure micro-displacement and micro-force and manipulate micro-particle without physical contact, so they have been used more and more in biological researches.

In biological research, optical tweezers typically need to manipulate biological specimen in a two-dimensional plane, which is perpendicular to the optical axis. In order to assure optical tweezers system of sufficient transverse stiffness, manipulate biological specimens rapidly, suppress Brown noise effectively, and improve measurement precision, the transverse trapping force should be increased as high as possible while the axial stability of the system is still kept.

The trapping force of an optical tweezers system will be directly affected by the adopted laser beam intensity profile. The advance of diffraction optics makes it possible to modify light beam profiles conveniently. A homogeneous dielectric sphere model has been used to calculate trapping force, and the effect of the light intensity distribution on it was analyzed and calculated in detail with ray-optics theory. The results indicate that the transverse trapping force of optical tweezers can be increased effectively through modifying laser beam intensity profiles.

Ⅱ. THEORY MODEL AND ALGORITHM

Calculation of the trapping force can be performed with either a ray-optics(RO) model[1] or an electromagnetic(EM) model.[2] Since the RO model follows the laws of geometrical optics, it is applicable to large particles whose dimension is far larger than the adopted laser wavelength. In contrast, the EM model is suited for small particles whose dimension is far smaller than the adopted laser wavelength. Results of the experiments mentioned in Refs.[3—6] indicate that the trapping force is in good agreement with the RO model when the sphere diameter is one order of magnitude larger than the adopted laser wavelength. In contrast, it is in good agreement with the EM model when the sphere diameter is smaller than the adopted laser wavelength.

In this paper, the particle manipulated is idealized as a homogeneous dielectric sphere, and the RO model is adopted to calculate the trapping force. The relation between the trapping force F and laser power p can be written as[1]:

$$F = Qn_1 p/c\,, \tag{1}$$

where Q is a dimensionless efficiency parameter, n_1 is the refractive index of the surrounding medium, and c is the speed of light in free space.

From Eq.(1) it is seen that the trapping force can be increased by increasing Q, n_1 or p. The surrounding medium is usually in some form of culture medium and generally cannot be altered without adversely affecting the specimen. In order to avoid thermal damage of the sample, the laser power p should be limited. The remaining term Q is then essential to the increase of trapping force.

In Fig.1 y and z are assumed to be the horizontal and axial directions, respectively, and the sphere center is assumed to be the origin. The scattering force f_s points to the direction of the incident ray, while the

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gradient force f_g is perpendicular to the direction of the incident ray. From Eq.(1) it is seen that f_s and f_g are proportional to Q_s and Q_g, respectively. They can be expressed as[1]:

$$Q_s = 1+R\cos 2\theta-\frac{T^2[\cos 2(\theta-\theta')+R\cos 2\theta]}{1+R^2+2R\cos\theta'}, \quad (2)$$

$$Q_g = R\sin 2\theta-\frac{T^2[\sin 2(\theta-\theta')+R\sin 2\theta]}{1+R^2+2R\cos\theta'}, \quad (3)$$

where R, T, θ and θ' are the reflection and transmission coefficients, the incident and refractive angles at the boundary of sphere, respectively.

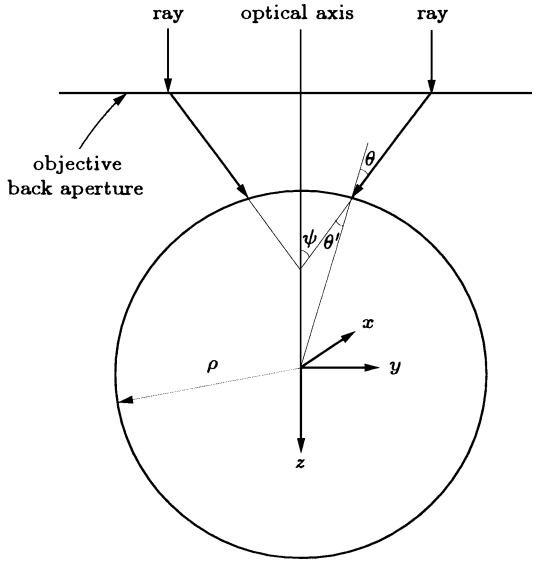


Fig.1. RO model for calculating trapping force.

The trapping force of a single ray can be calculated using Eqs.(2) and (3). The total trapping force on the sphere consists of the contributions of all the rays entering the objective back aperture.

Ⅲ. ANALYSIS AND CALCULATION OF THE TRAPPING FORCE

In the calculation of trapping force, it was assumed that the maximum convergence angle of the objective was 70°, and the intensity of light beams entering the back aperture was uniformly distributed. Due to the symmetry of the input laser beam the total trapping force on the sphere was clearly independent of the direction of polarization, and it could be assumed that the input beam was circularly polarized.

Trapping force on a dielectric sphere of relative refractive index $n = n_2/n_1 = 1.2$ was calculated in terms of Eqs.(2) and (3) when the laser beam was focused on y and z axes, where n_1, n_2 were the absolute refractive indexes of the surrounding medium and the sphere, respectively. The calculation was carried out by moving the laser focus along the y and z axes, respectively. The positions of the maximal trapping forces were found at ($y = 0.98\rho$, $z = 0$), ($y = 0$, $z = 1.01\rho$) and ($y = 0$, $z = -1.05\rho$), and the corresponding Q were 0.31, 0.28 and −0.49, respectively, where ρ was the sphere radius. The positive (negative) sign of the Q indicates the direction of trapping force pointing to $z(-z)$ axis. It is seen that the trapping force along $-z$ axis is larger than that along z axis, and it is symmetric about z axis when the trap is focused in the x-y plane, so we need only to calculate and analyze the trapping forces along the y and z axes.

Moreover, we have examined the dependence of trapping force on the intensity distribution of incident laser. We assume that the intensity profile of the beam is a perfect ring with a radius r, and then the trapping force is calculated by varying r from 0 to the edge of the objective back aperture.

In Figs.2 and 3 the numerical curves indicate that the values of Q are seriously affected by the radius r of the ring when the laser trap is focused on the points of ($y = 0.98\rho$, $z = 0$) and ($y = 0$, $z = 1.01\rho$), respectively, which give the variations of transverse and axial forces.

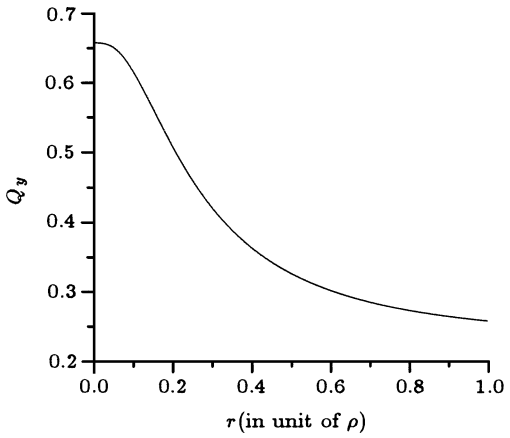


Fig.2. Q_y versus r.

From Figs.2 and 3 it is seen that the light rays nearby the center of the objective back aperture have greater contribution to transverse force, while those nearby the edge affect mainly axial force. Therefore, the axial force can be increased by distributing more light energy on the edge of the objective back aperture. On the contrary, the transverse force can be enhanced by distributing more light energy on the center.

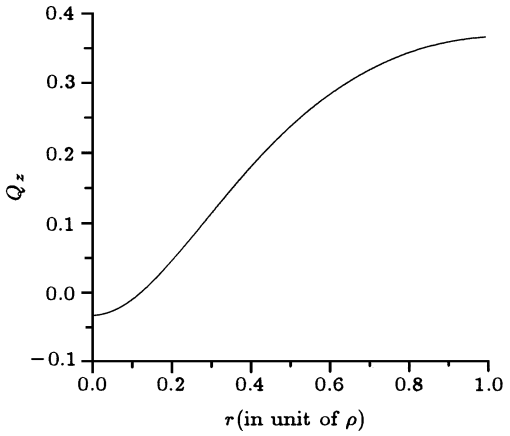


Fig.3. Q_z versus r.

When an optical tweezers system is operated in three-dimensional space, we should consider both the transverse and axial forces to make the particle stable. For example, in the measurement of movements and forces of a single myosin, the transverse trapping force of optical tweezers should be as high as possible while the axial stability of the system is still assured. It will directly affect noise subdual and the response speed of the system to the position displacement of the object manipulated.

Presently, the laser with TEM_{00} mode is widely used in optical tweezers. If the ratio of the laser beam radius to the objective back aperture is 1, the maximal Q_y and Q_z can reach 0.35 and 0.23 when the trap is focused on y axis and z axis, respectively. The experiments indicate that dielectric particles can be captured steadily with such a Gaussian mode[6], so we look for the proper intensity profiles of the laser beam, by which Q_z is not less than 0.23 and Q_y is as high as possible.

The calculations indicate that the maximal Q_y and Q_z can reach 0.41 and 0.23 when 36% and 64% of the total light energy can be idealy distributed on the center point and the edge ring, respectively.

Practically, the diffraction optics can be utilized to modify the laser profile to satisfy our need. In order to control the light energy distribution between the edge and the center the Gaussian mode can be modified into a dual-Gaussian mode, where the intensity distribution on the objective back aperture can be written as:

$$I(r) = \begin{cases} mI_0 \exp(-2r^2/w_0^2) & 0 \le r \le 0.5D\,, \\ I_0 \exp[-2(1-r)^2/w_0^2] & 0.5D \le r \le 1.0D\,, \end{cases} \tag{4}$$

where m is a dimensionless parameter, w_0 is the centric beam radius, D is the radius of the objective back aperture.

From Eq.(4) it is seen that the intensity distribution on the objective back aperture is determined by m and w_0. The beam radius w_0 determines the concentration of the light energy; and m is used to control the ratio of the light energy between the center and the edge of the objective back aperture, when w_0 is far smaller than D. We have calculated the values of Q as a function of m when $w_0 = 0.1D$, $0.2D$, and $0.3D$, respectively. The maximal Q values are given in Fig.4, where $Q_{y\max}$ and $Q_{z\max}$ are the maximal Q when the trap is focused on y and z axis, respectively.

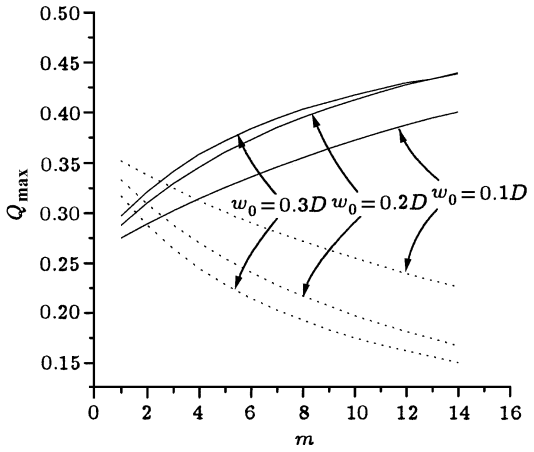


Fig.4. $Q_{\max}$ versus light energy distribution. The solid and dotted lines indicate $Q_{y\max}$ and $Q_{z\max}$, respectively.

From Fig.4 it is seen that $Q_{y\max}$ increases gradually while $Q_{z\max}$ decreases as the parameter m enhances. Similar dependences of Q on w_0 are found as long as m is not too large. As m increases, more light energy will be distributed on the center of the objective back aperture, in addition, the influence of w_0 becomes more serious.

The calculations show that $Q_{y\max}$ can reach 0.40, 0.39 and 0.37 while $Q_{z\max}$ keeps 0.23, when w_0 and m are, respectively, taken to be $0.1D$, 14; $0.2D$, 7; $0.3D$, 5, where 37%, 38% and 40% of the light energy are distributed on the center of the objective back aperture, respectively. The corresponding intensity distributions are given in Fig.5. From Fig.5 it is seen that increasing m benefits to concentrate more light energy on the center of the objective back aperture and improve the transverse stability.

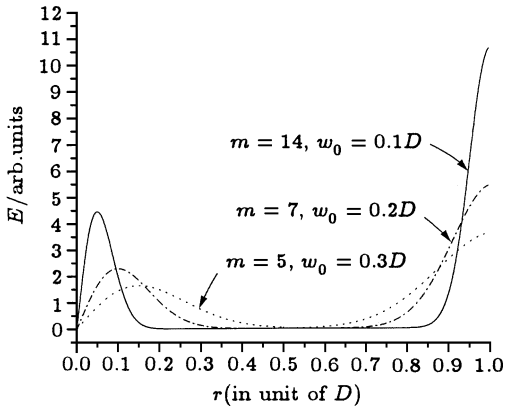


Fig.5. Intensity distribution of incident beam for three pairs of m and w_0.

IV. CONCLUSION

The trapping force has been analyzed and calculated in detail for a homogeneous dielectric sphere model. The results indicate that transverse stability of an optical tweezers system can be increased effectively through modifying laser beam profile. When the axial stability of the system is still assured, the $Q_{y\,\max}$, which is proportional to the maximal transverse force, can reach 0.40. In comparison with TEM_{00} mode of intensity distribution, the transverse force can be enhanced by 14% with the dual-Gaussian mode proposed, so that the transverse stability, the noise subdual and the response speed to the position displacement of the object manipulated will be greatly improved.

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