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EFFECT OF SPHERICAL ABERRATION INTRODUCED BY WATER SOLUTION ON TRAPPING FORCE*

YAO XIN-CHENG(姚新程)[a], LI ZHAO-LIN(李兆霖)[a], GUO HONG-LIAN(郭红莲)[a], CHENG BING-YING(程丙英)[a], HAN XUE-HAI(韩学海)[b], and ZHANG DAO-ZHONG(张道中)[a]

[a] *Optical Physics Laboratory, Institute of Physics and Center for Condensed Matter Physics, Chinese Academy of Sciences, Beijing 100080, China*

[b] *State Key Laboratory of Biomacromolecules, Institute of Biophysics, Chinese Academy of Sciences, Beijing 100101, China*

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Trapping force of an optical tweezers system with an oil immersion objective is calculated with a ray-optics model. Results indicate that the trapping force will be decreased as a result of the introduction of spherical aberration, which is caused by the refractive mismatch between objective oil and water, when the sample manipulated is suspended in a water solution. The effect of spherical aberration will be serious when the detection depth of the optical tweezers is enhanced.

Keywords: spherical aberration, optical tweezers, trapping force
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I. INTRODUCTION

A technological tool revolution has come forth in biological research because of the invention of optical tweezers. With an optical tweezers system, the biological sample, which is suspend in certain solution, can be manipulated without physical contact. In general, the refractive index of the solution is close to that of water. Aberration emendation of conventional objective system with standard cover slip is accomplished. However, spherical aberration will be introduced when a biological sample, which is suspended in water solution, is manipulated by an optical tweezers system with an oil immersion or a dry objective. Usually, an oil immersion objective with high numerical aperture (NA) is used in optical tweezers system to get large gradient force.

The effect of spherical aberration on imaging has been discussed in some papers,[1–3] and experiments[4] have been designed for investigating transverse trapping force. In Ref.[4] the three-dimensional intensity-point-spread-function was used to explain the experimental results, and a possibility for a further improvement in the trapping efficiency by using an objective of an infinitely-long tube length was proposed. Nevertheless, no one has calculated trapping force quantitatively in the presence of spherical aberration.

Calculation of the trapping force can be performed with either the ray-optics(RO) model[5] or electromagnetic(EM) model.[6] In this paper, the RO model is adopted to calculate the trapping force. The particle manipulated, which is suspended in water solution, is idealized into a homogeneous dielectric sphere and the change of trapping force is considered as a function of detection depth.

II. THEORY

The relation between the trapping force F and laser power p can be written as[5]

$$F = Qn_1p/c. \tag{1}$$

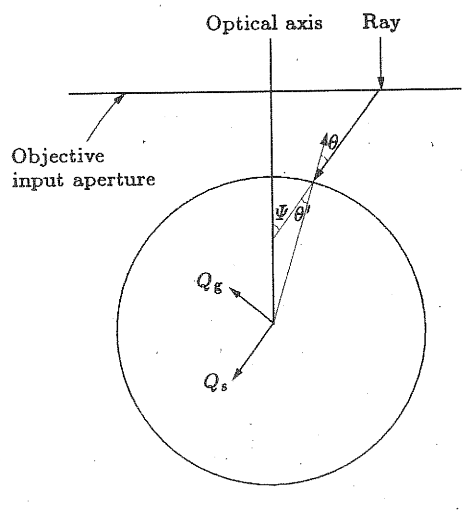

Fig.1. Dielectric sphere model for calculating trapping force.

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.

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In Fig.1 the scattering force f_s points to the direction of the incident ray, while the gradient force f_g is perpendicular to 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:[5]

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

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

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

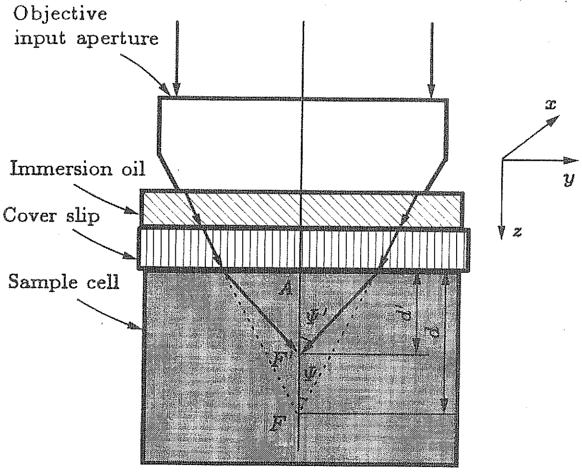

Fig.2. Sample suspended in a water solution is manipulated by an optical tweezers.

As a rule, an oil objective with $NA > 1$ is used in optical tweezers when three dimensional manipulation is required. In Fig.2 F and F' are the ideal and actual focuses. d and d' are the distances from the points F and F' to the surface of the sample cell. The relations between them can be written as

$$d\tan\Psi = d'\tan\Psi', \quad (4)$$

$$n_1\sin\Psi = n_2\sin\Psi', \quad (5)$$

where n_1,n_2 are the refractive indices of the objective oil and the water solution, respectively. Ψ, Ψ' are the ideal and actual convergence angles as illustrated in Fig.2.

Aberration emendation of the objective system with standard cover slip is assumed to be perfect. A parallel laser beam is converged by the objective system, and the rays with different Ψ will have a common focus F when $n_1 = n_2$. In practice, they have different focuses because $n_1 \neq n_2$. These different positions can be calculated with Eqs.(4) and (5).

It is obvious that total trapping force on the dielectric sphere consists of the contributions of all rays entering the objective input aperture. Q_s and Q_g of each ray can be calculated with Eqs.(3) and (4), and we refer to Ref.[5] to compute the relative R, T, and θ'.

III. CALCULATION AND ANALYSIS

In the calculation of trapping force, we make the assumptions: (a) an oil immersion objective obeying sine condition with $NA = 1.3$ is used; (b) the manipulated sample is a 2μm diameter polystyrene sphere; (c) the intensity distribution on the objective input aperture is uniform; (d) due to the symmetry of the system studied the total trapping force on the sphere is independent of the direction of polarization, and it could be assumed that the input beam is circularly polarized.

In Fig.2 y and z are assumed to be the horizontal and vertical directions, respectively, and the point A is taken as the origin. The detection depth $d = 10\mu$m is taken as an example to investigate the trapping force.

In the first instance, the trapping force is calculated when the sphere center moves along z axis. As a result of the symmetry the net force is axial. In Fig.3 the positive (negative) sign of Q indicates that the trapping force points to the z ($-z$) direction, and the solid (dotted) line represents the actual (ideal) trapping force respectively.

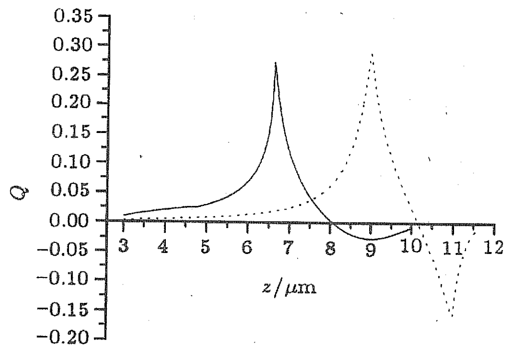

Fig.3. Trapping force on the sphere when it moves along z axis.

Moreover, the trapping force is considered when the sphere center moves in the transverse plane. In Fig.3 it is found that points ($y = 0$, $z = 8.0$) and ($y = 0$, $z = 10.2$) are the actual and the ideal balance positions of the sphere, respectively. We take accordingly points ($y = 0$, $z = 8.0$) and ($y = 0$, $z = 10.2$) as the relative origins of the transverse xy planes. Due to the symmetry one only needs to calculate the trapping force with the center of the sphere moving along

y. Again, in Fig.4, the positive sign of the Q_y (Q_z) indicates that the trapping force points to the y (z) direction, and *vice versa*; and the solid (dotted) line represents the actual (ideal) trapping force acting on the sphere.

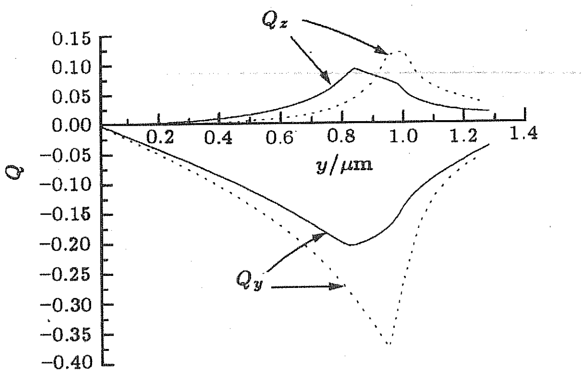

Fig.4. Trapping force on the sphere when it moves along y axis.

In Figs.3 and 4 it is found that the trapping force decreases because of the spherical aberration, and the balance point moves toward the surface of the sample cell. The slope of the trapping force line indicates the stiffness of the optical tweezers system, which plays a dominant role in the stability of optical tweezers. From Figs.3 and 4 we can see that the stiffness around the balance point decreases when the spherical aberration exists.

In addition, Fig.3 shows that the maximum trapping force pointing to z is larger than that pointing the other way, so $Q_{z\max}$, which is the maximum of the absolute value of the trapping force pointing away

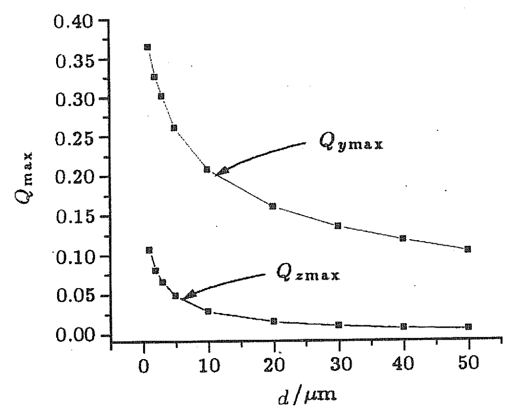

Fig.5. Trapping force curves vs. detection depth.

from z, can be taken as an indication of the axial trapping force. Similarly $Q_{y\max}$ can be taken as an indication of the transverse trapping force. The relation between $Q_{y\max}(Q_{z\max})$ and d is given in Fig.5, where the sign of $Q_{y\max}(Q_{z\max})$ has been omitted.

From Figs.3, 4 and 5 it is seen that $Q_{y\max}$ is larger than $Q_{z\max}$, so the axial stability is essential to the system stability, and it is obvious that the effect of spherical aberration will be serious when the detection depth of the optical tweezers increases.

IV. CONCLUSION AND DISCUSSION

The foregoing analysis shows that the trapping force will decrease with the introduction of spherical aberration when an oil immersion objective is used, and the effect of spherical aberration will be evident while increasing the detection depth. The maximum of trapping force pointing away from z can be taken as an indication of the axial trapping force because it is smaller than that pointing to z. The axial stability is dominant to the stability of an optical tweezers system because $Q_{y\max}$ is larger than $Q_{z\max}$. With the detection depth increasing, the axial trapping force will decrease more seriously than the transverse trapping force. For example, when a $2\mu m$ diameter polystyrene sphere is trapped at the detection depth $d = 50\mu m$, the axial trapping force and the transverse trapping force will decreased to 2.8% and 27.4%, respectively, of that when it is trapped at the water solution surface. In experiments, we found that the instability will be serious when the detection depth increases. It is in accord with the result of theoretical analysis. In order to ensure the stability of an optical tweezers, the detection depth should be limited to a tolerable range.

Several methods can be applied to eliminate the effect of spherical aberration. It is feasible to change the active tube length[2,4] or design special objective for a certain detection depth , but it is unfit for a system which needs to vary the detection depth in a large range continuously. A water immersion objective is recommended to avoid the introduction of spherical aberration.

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