Study on the response characteristics of adaptive focusing system for flying optics

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The *ABCD* law of parameter q for fundamental-mode Gaussian beam is deduced in this paper. The result shows that the changes of focal length and focal depth are not related to the orders of the Gaussian beam modes when focus lens moves along optical axis in a large range, indicating that the *ABCD* law of parameter q can be used for any order modes. A laser focusing setup is designed, and the response characteristics of oil pressure system therein are also studied.

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Recently, the study on the focus characteristics of laser beam has been paid much attention[1]. In general, the quantities reflecting the laser focus characteristics include the difference between the real focal length and the geometric focal length, focus spot size, and focal depth. It is well known that the focus characteristics of laser beam are of great importance in the fields such as laser processing, the spatial filter in large laser projects, laser target shot, CD engraving, laser space craft vehicles, and so on. The theoretical and experimental studies of laser focus and the treatment of the related problems become a subject of practical significance to laser technique and its applications.

When a super-large, super-weighted workpiece is processed, the focus lens moves a long distance along the optical axis, which makes the focus characteristics change greatly. Usually the change of focal length is in the order of several millimeters, which makes it impossible to cut and weld in laser processing.

In recent years, deformable mirror has been developed and widely used in laser engineering[2]. At present, the focus is usually adjusted by mechanically changing the position of mirror, and this method requires a very high precision in the mechanical processing of focus system. M. Bea[3] reported the research on deformable mirror in flexible focus system by water pressure system in laser processing. However, little work has been reported on the response characteristics of the system. In this paper, a method is introduced to change the curvature radius of reflector by injecting oil into the reflector, which can change the focal length of the reflector precisely. The flexible focus system has much better performance than mechanical ones. Based on the research of the focusing characteristics of flying optics, the relations between the focal length (f) of adaptive mirror and flying distance (L), between the pressure change and flying distance, and between the pressure change and response time are studied theoretically and experimentally.

It is difficult to get a pure fundamental mode (TEM_{00}) in a high power CO_2 laser. Usually, the output is the mixture of TEM_{00}, low-order and high-order modes[4]. The main optical parameters are laser beam waist radius size w_{mn}, beam divergence half angle θ_{mn}, and Rayleigh range Z_{R}. The following expressions are familiar in laser optics

$$w_{mn} = M w_{00}, \tag{1}$$

$$\theta_{mn} = M \theta_{00}, \tag{2}$$

$$Z_{\mathrm{R}} = \frac{\pi w_{mn}^2}{M^2 \lambda}, \tag{3}$$

$$w_{mn}\theta_{mn} = M^2 \cdot w_{00} \cdot \theta_{00} = M^2 \cdot \frac{\lambda}{\pi}, \tag{4}$$

where w_{00} is the waist radius of TEM_{00}, M^2 is the beam quality factor, and λ is the beam wavelength.

In most applications, laser beam is used after focused by lenses or mirrors. Focusing the Gaussian beam is the same as imaging of its waist. For a TEM_{00} mode, complex parameter $q_{00}(z)$ can be expressed as

$$\frac{1}{q_{00}(z)} = \frac{1}{R_{00}(z)} - \frac{i\lambda}{\pi w_{00}(z)}, \tag{5}$$

where $R_{00}(z)$ is the curvature radius, and $w_{00}(z)$ is the beam radius at point z. After transformed by an optical system (such as a focus lens), its complex parameter $q'_{00}(z)$ can be expressed as

$$q'_{00}(z) = \frac{A q_{00}(z) + B}{C q_{00}(z) + D}, \tag{6}$$

where A, B, C, D are the matrix elements of the optical system. The transform matrix is written as

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & f' \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{bmatrix} \begin{bmatrix} 1 & z - z_0 \\ 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 1 - f'/f & (z - z_0) - \frac{f'}{f}(z - z_0) + f' \\ -1/f & 1 - \frac{(z - z_0)}{f} \end{bmatrix}, \tag{7}$$

where f' is the real focal length.

From the above analysis, the *ABCD* law of q parameter is only valid for the TEM_{00} mode of Gaussian beam, and the study of the focus characteristics is equivalent to the imaging of the beam waist. Under this condition, the radius of curvature $R_{00}(z)$ is infinite and w_{00} is the waist radius of TEM_{00} at position z_0 as shown in Fig. 1.

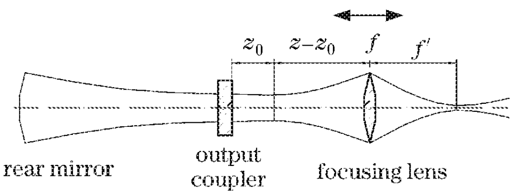

Fig. 1. The model for focusing system in flying optics.

$q_{00}(z)$ is written as q_{00}. Equation (5) can be written as[1]

$$\frac{1}{q_{00}} = \frac{-i\lambda}{\pi w_{00}^2}. \tag{8}$$

For the TEM$_{00}$ mode, the divergence angle $\theta_{00} = \frac{\lambda}{\pi w_{00}}$. From Eqs. (1) and (2), we can obtain

$$\frac{1}{q_{mn}} = -i \cdot \frac{\theta_{mn}}{w_{mn}}, \tag{9}$$

where w_{mn} and θ_{mn} are the waist radius and divergence angle of the TEM$_{mn}$ mode of the Gaussian beam, respectively. From Eqs. (3) and (4), for a certain resonator, the Rayleigh range is expressed as

$$Z_{\mathrm{R}} = \frac{w_{mn}}{\theta_{mn}}. \tag{10}$$

Substituting Eq. (10) into (9), the *ABCD* law of q parameter (6) can be extended to any order Gaussian modes (i.e. TEM$_{mn}$ modes, here m and n are arbitrary nonnegative numbers) as

$$\frac{1}{q_{mn}} = \frac{-i}{Z_{\mathrm{R}}}. \tag{11}$$

Combining Eqs. (6), (7), and (11), we can give the focus characteristics of any order modes of Gaussian beams. The difference Δf between the real focal length f' and the geometric focal length f, the focus spot diameter d, and the focal depth (the new Rayleigh range) h, can be obtained, respectively as

$$\Delta f = f^2(z - z_0 - f)/[Z_{\mathrm{R}}^2 + (z - z_0 - f)^2], \tag{12}$$

$$d^2 = \frac{4\lambda}{\pi} \cdot M^2 f^2 Z_{\mathrm{R}}/[Z_{\mathrm{R}}^2 + (z - z_0 - f)^2], \tag{13}$$

$$h = f^2 Z_{\mathrm{R}}/[Z_{\mathrm{R}}^2 + (z - z_0 - f)^2], \tag{14}$$

where h is defined as the axial distance when spot size is changed to $\sqrt{2}$ times of its focus size, i.e. the new Rayleigh range of the Gaussian beam focused.

From Eqs. (12)−(14), several important conclusions can be reached: under the condition that the thermal distortion of the mirrors and the work medium of the resonator can be omitted, the Rayleigh range is not related to the orders of the Gaussian beam, i.e. $Z_{\mathrm{R}} = \frac{w_{mn}}{\theta_{mn}} = \frac{w_{00}}{\theta_{00}}$. When the focus lens moves along the optical axis for a long distance, one pays the most attention to that how to change the difference between the real focal length and the geometric focal length. From Eq. (12), we know that when the location z of the focus lens or mirror satisfies $z = Z_{\mathrm{R}} + (z_0 + f)$, Δf reaches its maximum

$$\Delta f_{\max} = f^2/(2Z_{\mathrm{R}}). \tag{15}$$

For certain stable resonator, Eq. (15) can be used for any order modes.

On the basis of the above theoretical study, a self-adaptive focusing optical system was designed, as shown in Fig. 2, to eliminate the flying optical effect on spot size and focus radius in laser processing when the workpiece moves a large range. The system consists of an adaptive concave mirror and an adaptive convex mirror. First a lens is fixed a distance after the laser, and then two deformable mirrors and a focus mirror are integrated as the focusing system moving along the direction of the arrow. In order to keep the focal length and spot size in flying optics constant, there must be two independent variables, which change with the moving range. The focal lengths of lens, DM$_1$, DM$_2$, and PM are f_0, f_1, f_2, and f_3, respectively. L_0 is the distance between output beam waist and lens. L' is the distance between focusing point and PM. L_1 and L_2 are respectively the distances between DM$_1$ and DM$_2$, and between DM$_2$ and PM. L is flying distance.

If the imaging aberration caused by the slant input beam is neglected, we can make an equivalence of lenses to the system shown in Fig. 2, and with Fig. 3 being the sketch of the equivalence. The propagation matrix of the self-adaptive system shown in Fig. 2 is given as

$$\begin{aligned}\begin{bmatrix} A & B \\ C & D \end{bmatrix} &= \begin{bmatrix} 1 & L' \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 \\ \frac{-1}{f_3} & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & L_2 \\ 0 & 1 \end{bmatrix} \\ &\cdot \begin{bmatrix} 1 & 0 \\ \frac{-1}{f_2} & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & L_1 \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 \\ \frac{-1}{f_1} & 1 \end{bmatrix} \\ &\cdot \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 \\ \frac{-1}{f_0} & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & L_0 \\ 0 & 1 \end{bmatrix}\end{aligned} \tag{16}$$

In Eq. (16), f_1 and f_2 are variables changing with the change of curvature of deformable mirror. The distance

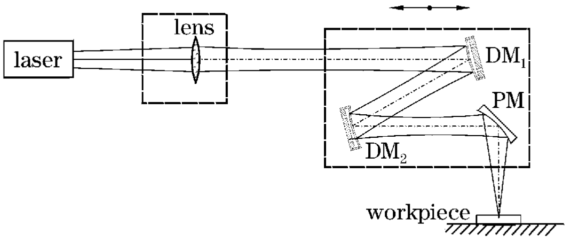

Fig. 2. The sketch of the self-adaptive system.

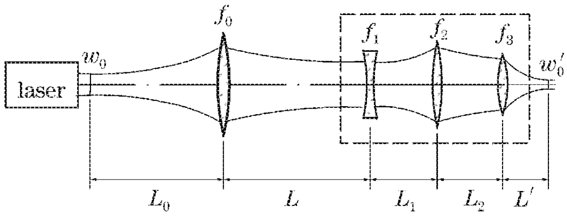

Fig. 3. The equivalence in lens of the system shown in Fig. 2.

L is also variable, and other parameters are all known in actual applications. Thus the elements of matrices A, B, C, and D, which contain the variables of f_1, f_2, and L can be calculated.

Take the high power laser processing as an example. The parameters of the system are chosen as follows. The focal length of focusing mirror $f_3 = 130$ mm, focusing length $L_\mathrm{f} = 131$ mm, the difference between focal length and focusing length $\Delta f = 1$ mm, the focusing spot size $w' = 0.15$ mm, the changing curve of f_1 and f_2 with the change of flying distance L can be obtained through numerical simulation, the results are shown in Fig. 4.

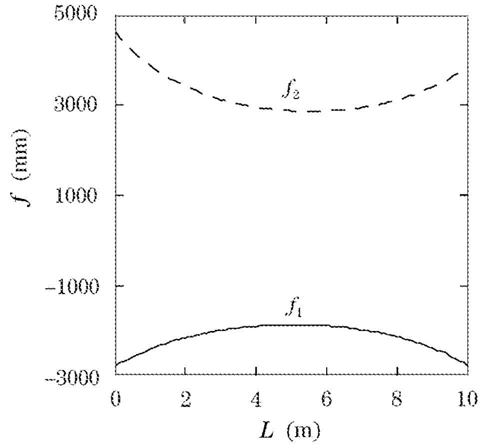

Fig. 4. The relation between flying distance L and focal length f.

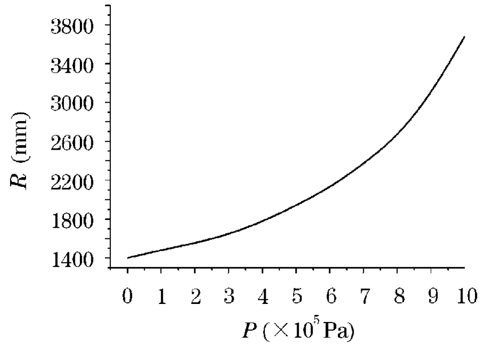

Fig. 5. The relation between pressure P and curvature radius R for concave mirror.

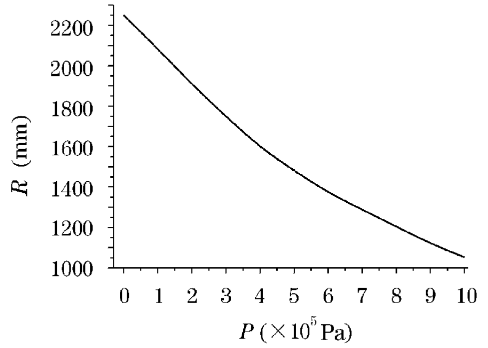

Fig. 6. The relation between pressure P and curvature radius R for convex mirror.

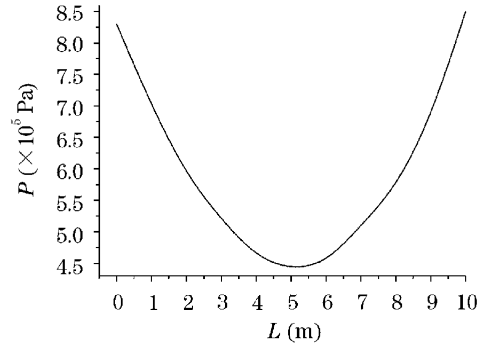

Fig. 7. The relation between pressure P and flying distance L for concave mirror.

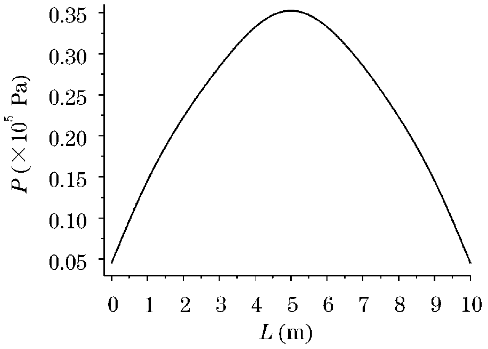

Fig. 8. The relation between pressure P and flying distance L for convex mirror.

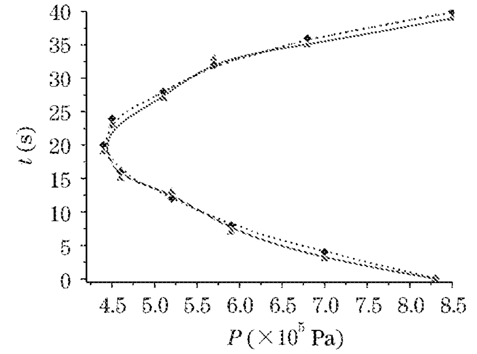

Fig. 9. The theoretical (dotted line) and experimental (solid line) relation between the response time t and pressure P for concave mirror.

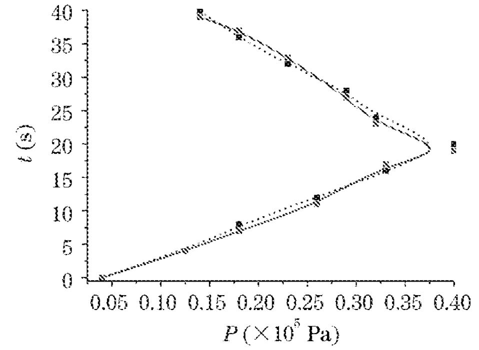

Fig. 10. The theoretical (dotted line) and experimental (solid line) relation between the response time t and pressure P for convex mirror.

When the laser focus control meter moves along optical axis, and if we keep focus spot size and its position constant after focusing, the curvature radius of deformable mirror can be made constant by changing the oil pressure because of the change of flying distance. At the same time, it can meet processing demands when the response frequency of focusing system higher enough so that the practical response time is shorter than or equal to the theoretically expected time within flying distance.

We have tested the relations between pressure and focal length for concave mirror and convex mirror, and the results are shown in Figs. 5 and 6, respectively. Figures 7 and 8 are the relations between the pressure and flying distance for concave mirror and convex mirror, respectively. They are calculated from Figs. 4 – 6.

If the speed of cutting and welding is 15 m/min in laser processing, we can get the relation between the response time and the pressure by theoretical calculation and experimental measurement. In Figs. 9 and 10, the dotted lines are theoretical curves, the solid lines are experimental curves. In fact, the speed of cutting and welding is usually 1 – 3 m/min in laser processing, the actual response time is less than the theoretical response time. So it can satisfy the actual need, and has the important significance in laser processing.

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