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Real Time Measurement of Subgrade Settlement in High Speed Railways with a Resolution of 0.25 mm Using a Laser Imaging Method

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A new technique based on the property of laser is developed to measure subgrade settlement with high accuracy and resolution. In this technique a laser mounted on the subgrade produces a horizontal beam and is received and imaged by a charge-coupled device (CCD). When the subgrade settlement occurs, it results in a displacement of the image on the CCD. By measuring the displacement one can monitor the settlement *in situ* with high accuracy. Using a laser beam rather than a light emitting diode (LED), the CCD can receive a high brightness spot. This makes the system working effectively during daytime despite the interference of sunlight and makes it possible to detect the settlement when the distance between the laser and the CCD is 40 m. By laser beam shaping, the image on the CCD is nearly rounded so that the CCD can read its position easily and improve the resolution of the system. The system is designed to work in the field and it works normally under moderate atmospheric turbulence both experimentally and theoretically. So, the system enjoys some promising merits such as high accuracy, high resolution, low environmental influence factor and high signal-to-noise ratio (SNR). The resolution of the system depends on the focal length of the lens used. With a cemented doublet of focal length 1000 mm, the resolution is 0.25 mm or better and the theoretical calculations agree well with the experimental data.

Keywords: Laser beam, charge-coupled device (CCD), railway, laser measurement, subgrade settlement, high brightness, displacement distance, safety

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1 INTRODUCTION

With the rapid development of high speed rail construction in China, the security and safety of high speed rail has attracted more and more attentions in the recent years. For the high speed rails, the subgrade settlement has become an inevitable issue. The settlement can be induced by inappropriate selection of the construction material, inappropriate filling pattern and constructional methods, so the compactness of the rail may not be good enough and it leads to the settlement of subgrade as time goes on. The statistics by China's high speed rail Corporation shows that a small subgrade settlement of 3 cm *per* 20 m in a high speed railway would cause significant discomfort to the passenger; moreover, it even poses the potential threaten to the safety of the high speed train.

Subgrade settlement rate needs to be monitored and there are strict regulations to control the settlement of subgrade and the different countries have different standards and regulations; for example, the limit of allowed subgrade settlement rate of Shinkansen in Japan is 3 cm *per* year, while this number is 2 cm *per* year in China. In order to monitor the extent and tendency of the settlement, the settlement detection is an essential step. To this end, the real-time monitoring of the settlement with improved accuracy and sensitivity has become one of the most important jobs in the construction and maintenance of high speed railways. Currently, the methods available for measuring subgrade settlement are multifarious, such as the traditional monitoring technology on civil engineering [1-3], the optical measurement method using fiber Bragg grating (FBG) [4], GPS (global positioning satellite) technology [5] and the differential interferometric synthetic aperture radar (D-InSAR) [6].

But, all above mentioned methods have some disadvantages such as low resolution, low sensitivity and high cost; therefore making it difficult to perform long term *in situ* monitoring. Some methods can only be used at special places where the temperatures excess 0°C. Some of them are not suitable for busy and high speed railway sites due to poor vibration resistance [7-8]. In 2008, Zhang *et al.* [9] developed a real-time measurement system for subgrade settlement with the method of laser ranging. The system can obtain the value of subgrade settlement by measuring the distance between laser and the target. It has the advantages of easy to use and relative low cost in construction. The testing system is applied to an existent railway in a city to examine situation of subgrade settlement; however, the accuracy and resolution of the system cannot reach a satisfactory level, with the measuring error reaching up to ±2 mm. In 2010, Li *et al.* [10] developed a system of long range optical fiber displacement sensor to meet the requirements of the soft ground monitoring. But, this method shows strict requirements on the burying technology. In 2012, Yang and Feng [11] built a measurement device that mainly contains a light emitting diode (LED) point light source on a settlement detecting pile and a point-position measurement device that uses a linear charge-coupled device (CCD) to detect the position change of the point light's image. The subgrade settlement information can be sent to a computer in the office by using wireless technology, and remote measurement and monitoring of the subgrade settlement can be realized. But because of the divergence of the LED, the image on the CCD is too weak to be read by the CCD with high resolution, resulting in the limiting error reaching up to nearly 0.06 mm [11].

In this paper we present a new and efficient method for the measurement of subgrade settlement. A laser is fixed on the detecting base to simulate the real subgrade settlement. The laser beam propagates a long distance and is focused on the CCD, which yields the value of subgrade settlement by reading the displacement of image spot on CCD. Because of excellent directivity and high brightness of the laser beam, it allows long distance monitoring and daytime operation. The method not only can measure the subgrade settlement in real-time. It also improves the resolution to 0.25 mm at distance of 40 m, which is much better than the conventional methods.

2 EXPERIMENTAL SCHEME

2.1 Experimental principle

The diagram showing experimental principle of our system is shown in Figure 1. The laser is fixed on the settlement detecting base, fired horizontally and received by the CCD after propagated a distance and focused by a lens. The laser beam then forms a focal spot on the CCD, which is installed on the detection base. If there is a displacement of the laser beam due to the settlement, then there will be a displacement of the image spot on the CCD in the vertical direction.

The lens and CCD are laid on an unsinkable base, away from the railway, which has almost no settlement. The value of subgrade settlement can be obtained by reading the change of image spot position on CCD. The distances between laser and lens and between lens and CCD are set as S and S', respectively. Due to the divergence of the laser beam, its diameter of the laser beam increases with the distance propagated. The image size of the laser on the

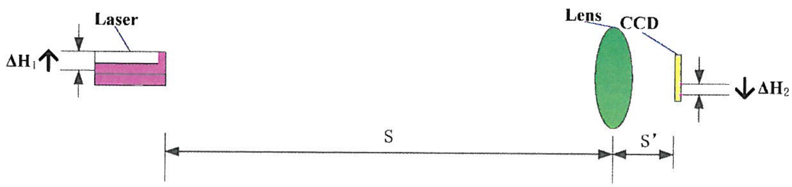

FIGURE 1
Schematic diagram of the experimental arrangement.

CCD can be minimized by adjusting the distance between the lens and CCD, the focal length f, so that the focal point of the laser beam is right on the CCD and so $S'=f$. At the focal plane, the image size, Φ, is approximately

$$\Phi=f\theta \tag{1}$$

where θ is the divergence of the laser beam. For a laser beam with a divergent angle of θ=1 mrad and a focal length f=1000 mm, the beam diameter is about 1 mm. In the case of vertical settlement, when the laser beam has vertical displacement of ΔH_1 due to the settlement, the height of the laser image spot on the CCD will have a displacement distance of ΔH_2 in the vertical direction. According to the geometry of the thin convex lens imaging set up, the relation between the settlement and the displacement of the focal spot on CCD can be written as [12]

$$\frac{S}{S'}=\frac{\Delta H_1}{\Delta H_2} \tag{2}$$

Using Equation (2), the subgrade settlement can be measured remotely with very high resolution and sensitivity.

2.2 Measurement methodology

In order to observe the experiment result we adopt a home-made laser whose wavelength was 632 nm and the divergence angle was 1 mrad. The focal length of the lenses used was 250 and 1000 mm to test the different resolutions of the system.

The detector was a CCD (CinCam; Cinogy Company). The pixel matrix was 1288 × 1032 and the receiving area was 6.7 × 5.3 mm^2. The resolution of the system depends both on the resolution and image size of the laser beam on the CCD.

In the experiments the laser was laid on a platform (M-561-UM; Newport Corporation), whose height was adjustable to simulate the subgrade settlement. The height of the laser was adjusted using a micrometer to stimulate the subgrade settlement while keeping the position of the CCD and the lens unchanged. The distance of S was 40 m and the S' was approximately equal to the focal length of the lens. Here, the displacement of the focused laser spot is observed through the CCD when the height of the laser beam is changing.

2.3 Experiment design and error analysis

2.3.1 Beam shaping

When a laser beam is used for precise measurements, the beam quality has great impact on the image size on CCD and it affects the resolution of the system.

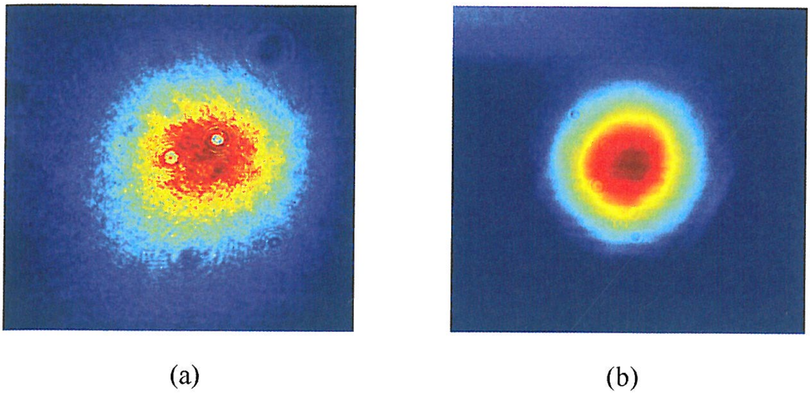

FIGURE 2
(a) Laser spot before improvement and (b) laser spot after improvement.

First, a lens with focal length of 250 mm was used in this experiment and the shape of the far-field spot of the laser is observed on the CCD. The result is shown in Figure 2(a) which shows that the shape of the laser is an irregularly ellipse. There are two main reasons that lead to the distortion of laser spot. One is due to the inherent defect of the laser. The shape of laser spot in the near field is also an ellipse, the same as which of the far field. In addition, the distortion of the laser image spot gets more serious with the increasing distance between lens and the laser device. So, the laser device itself has an important impact on the shape of the laser on CCD in the far field. The other is the spot size on the CCD, which is also under the influence of the diffraction of the far field in the air. There are a lot of tiny particles in the air and result in the diffraction of the laser beam in the far field. Therefore, the spot shape of the laser changes a significantly on the CCD and results in certain non-uniformity.

Taking into account these factors, a collimated beam with beam expanding optics is used to implement imaging of the laser beam. And then a circular aperture is added to the system through which the laser passes. There are two main advantages of this new system. One of the advantages is that the spot shape is controllable and forms a shape that is close to a circle on the CCD. Another advantage is that the divergence angle of the laser is reduced due to the collimating [13].

The images of the laser spot on the CCD after beam shaping is shown in Figure 2(b). According to the figure, the spot shape is nearly rounded. The energy distribution of a laser beam before beam quality improving is not homogeneous as illustrated in Figure 2(a) by the pseudo colour encoding. The main reason is the aberration of the lens. The object distance between the laser and lens is set as 40 m and the divergence angle is 0.8 mrad, which result

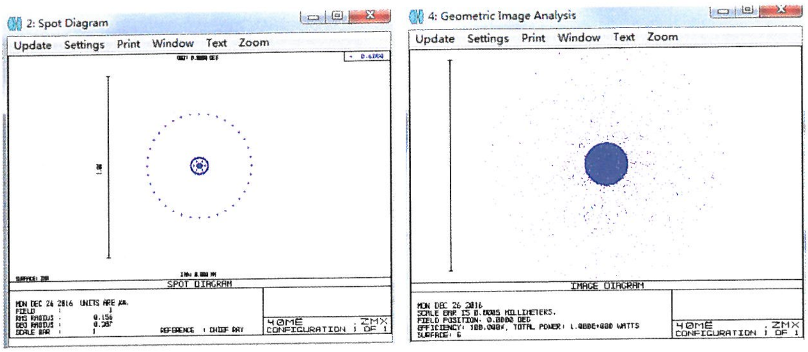

FIGURE 3
Spot diagrams on the CCD by ZEMAX simulation for (a) ray aberration and (b) geometric image analysis.

in a beam diameter on the lens is nearly 4 cm, and thus the beam size is too large to avoid severe aberration. Besides, there are several bright spots in the laser spot on the CCD. It is because of the fact that the system was not working in the laboratory, which suffered severely from the scattering of the particles in the air. The particles can block the propagation of the laser beam. After taking care of aberration and scattering, the laser spot on the CCD is demonstrated in Figure 2(b).

In order to improve the resolution of the system, according to Equation (2), a single convex lens and a cemented doublet whose focal lengths equal 250 and 1000 mm are used to for comparison. In the experiment, the cemented doublet is adapted to reduce the aberration and the ZEMAX simulation of the laser image on the CCD is shown in Figure 3. From Figure 3(a) we can see that the radius of the laser beam image is 0.287 μm, which proves resolution of the system compared with the situation without beam shaping. And the geometric image on the CCD is shown as Figure 3(b). From it, we can see that most of image points are concentrated at the centre, while the scattered points outside of the bright spot, which appear as the noise, are quite few and indicating a good signal-to-noise ratio (SNR).

Based on the simulation, the required distance between the lens and the CCD should be 1000 mm in order to improve the resolution of the system according to Equation (2) and the distance is too long to be used in any practical application. There are two ways to reduce the encapsulation length between the lens and the CCD. One is to use a lens group consisting of a convex lens and a concave lens whose focal points are overlapped so that the distance can be reduced. The other is to use two reflectors to fold the optical path of the laser beam to reduce the separation between the lens and the CCD, as shown in Figure 4.

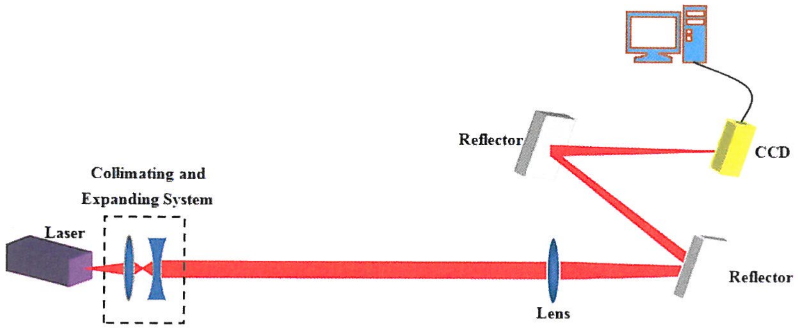

FIGURE 4
The schematic diagram of the experimental set up with beam reshaping.

2.3.2 The advantages of a long laser beam propagation distance

The previous optical methods such as using a LED and a CCD to measure the subgrade settlement can only be applied at night. Because of the high divergence of the LED, the CCD can only receive a very weak laser spot and the resolution of system is affected deeply by the noise of sunlight. As a comparison, a laser beam has the advantages of small divergent and high brightness, and the CCD can receive a high brightness spot; consequently, in the subgrade settlement measurement, especially in the daytime, it is particularly appropriate to use laser instead of the LED for subgrade settlement measurement.

Laser beam power is partially attenuated when it is propagating in the atmosphere. The attenuation is mainly come from two sources: One is absorption and the other is scattering. The attenuated power of laser received by the CCD in the experiment must be strong enough to be detected by CCD easily even during the daytime.

Figure 5 is a schematic representation of a laser spot when the laser beam propagation distance is L. When a laser beam propagates a long distance, the area of the laser spot, S_i, can be calculated by

$$S_i = \frac{1}{4}\pi L^2 \theta_i^{\,2} \tag{3}$$

When the beam of a laser spreads in the air, the power of the laser beam, P_s, will be attenuated exponentially and the laser power density as a function of distance can be written as

$$P_s = P_i S_i^{-1} e^{-\beta L} \tag{4}$$

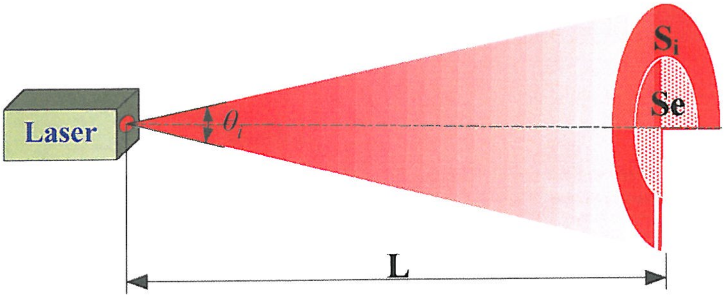

FIGURE 5
Schematic diagram of the spot when the laser beam spreads a distance of L.

where P_i is the initial power of laser and β is the attenuation coefficient [14]; in fact, the area of the laser spot, S_e, will be smaller than S_i because of the circular aperture. The real power of the laser beam, P_e, can be derived from

$$P_e = P_s . S_e = P_i (\frac{1}{4} \pi L^2 \theta_i^2)^{-1} e^{-\beta L} (\pi R^2) \tag{5}$$

where R is the spot radius after using a circular aperture. In the experiment the laser power will also attenuate if the lens is uncoated. So, the real laser power on the lens after traveling a long distance, P_r, is

$$\mathrm{P_r} = T_1 T_2 P_\mathrm{e} = T_1 T_2 P_i (\frac{1}{4} \pi L^2 \theta_i^2)^{-1} e^{-\beta L} (\pi R^2) \tag{6}$$

where T_1 and T_2 are the transmittance of the collimating beam expanding optical system and the lens, respectively.

In order to calculate the power of the laser beam on the lens, both of T_1 and T_2 are set as 0.9, β is 0.01, P_i is 20.00 mW, L is 40 m, θ_i is 1 mrad and R equals to 0.02 m. According to Equation (6) we can obtain that the power of the laser beam on the lens is 10.85 mW. The result shows that the power of laser focused on CCD are strong enough so that the CCD can read the position of spot easily and the system can be used in the daytime.

2.3.3 Image spot shaking induced by atmospheric turbulence

In the experiments, besides the influence of walking people and the noise, which all result in shaking of beam spot, the laser also has a series of linear and nonlinear effects arising from propagation of laser through air, especially after long distance propagation. The formal meteorological elements (flow

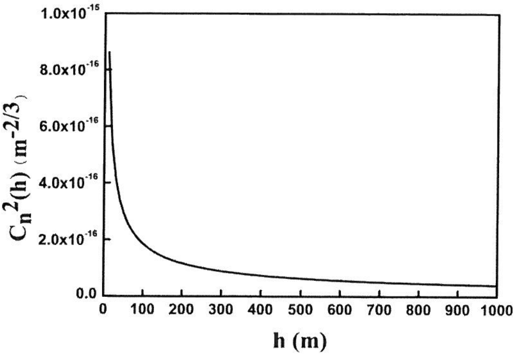

FIGURE 6
Curve of $C_n^2(h)$ *versus* laser beam height.

field, temperature, atmospheric pressure, humidity and visibility) and the atmospheric optical parameters such as atmospheric turbulence will cause irregular changes of atmospheric refractive index at different position and time. Thus, the laser spot will shake irregularly.

The effect of atmospheric turbulence on the laser transmission process is closely related to the spot diameter d_B and turbulence scale l. If $d_B/l<1$, the main effect of the turbulence lies in beam random drift. $C_n^2(h)$ can be used to present the turbulence intensity. The Hufnagel model is often used to simulate turbulence intensity ($C_n^2(h)$) at near ground level [15]:

$$C_n^2(h) = 4\times 10^{-15} h^{-2/3} \tag{7}$$

The calculated curve of Equation (7) is shown in Figure 6 in which we can see that the turbulence intensity is rather high of 10^{-15} orders of magnitude at near ground and then it will decrease exponential with the increase of height.

We can calculate the relationship between the laser drift variance and propagating distance from [14]

$$w^2 = 1.709 C_n^2 z^3 D^{-1/3} \tag{8}$$

where w is the drift radius, z is the spread distance and D is the diameter of the optical system. When z, C_n^2 and D are set as 40 m, 6.3496×10^{-15} and 0.001 m, respectively, solving Equation (3) simultaneously, the drift radius is 0.083 mm, as shown in Figure 7. So, according to Equation (2), the drift

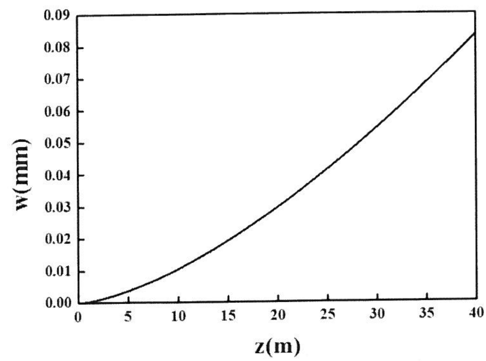

FIGURE 7
Curve of wander variance *versus* laser beam propagating distance.

radius on the CCD of laser image due to the perturbation of air is 0.002 mm. But, the calculation is suitable for the situation of strong atmosphere turbulence, while the real situation of the measurement is moderate atmosphere turbulence, so that the drift radius of the laser image will be reduced to some extent. So the atmosphere turbulence has little influence on the measuring result in our experiment.

3 RESULTS AND DISCUSSION

3.1 Experiments with f=250 mm lens

One set of experiments for measuring subgrade settlement we first used a lens with a focal length of 250 mm. The distance between the lens and the CCD was 250 mm. The experimental arrangement is shown in Figure 8 and the experimental results on image displacement on the CCD as a function of displacement of the laser beam due to the settlement are given in Figure 9. The increment of the laser beam height is 1 mm each time and the distance between the laser and the CCD is about 40 m. According to Equation (2), the slope of the line in Figure 9 should be 0.00625, but the measured value by the fitting of the experimental data is 0.0061 with an experimental error of 2.4%. The resolution for settlement detection of the system is measured to be 0.5 mm.

3.2 Experiments with f=1000 mm lens

One set of experiments for measuring subgrade settlement we used a lens with a focal length of 1000 mm. The distance between the lens and the CCD was 1000 mm. The height of laser was changed by 1 mm each time. The height of the laser and laser beam's image centre are shown in Figure 10 as

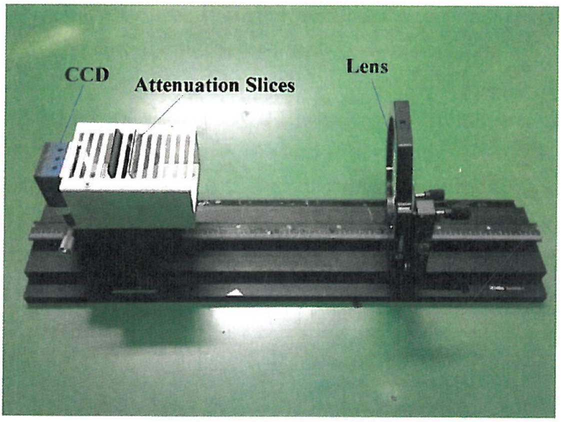

FIGURE 8
Photograph of the experimental set up. The distance between lens and CCD is the focal length of the lens. Attenuation slice and filter is settled between the lens and CCD. The attenuation slice is used to reduce the intensity of the laser beam to protect the CCD.

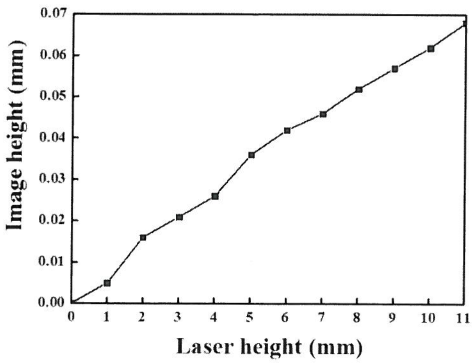

FIGURE 9
Graph showing the relationship between the height of the laser and laser beam's image centre by the f=250 mm lens.

the red line. In theory, the slope of the line in Figure 10 is 0.025. In other words, the laser spot should have a change of 0.025 mm by each movement. And the real slope of the line is 0.0245, which is almost identical with the theoretical value.

The resolution of the system using a lens with a focal length of 1000 mm was also tested and the corresponding resolution can be as good as 0.25 mm, as shown in Figure 10 as the black line. Of course, if we can eliminate the aberration of the lens on the spot, the resolution can be further improved. Because of the existence of lens aberration, the spot shape will not be a stan-

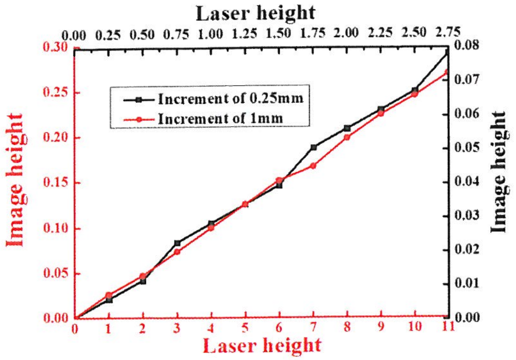

FIGURE 10
Graph showing the relationship between the height of the laser beam and image centre of the laser spot on the CCD using f=1000 mm lens. The black and red spots represent the experiment data by the increment of laser height of 0.25 mm and 1 mm, respectively.

dard rotundity and the energy distribution will not be uniform. If such aberration can be reduced, the space resolution can be further improved [16].

In the experiments we found that the value of the laser spot position on the CCD is still fluctuating. The fluctuation can be attributed mainly to the following two reasons: First, due to the turbulence in the air, so that the CCD usually receives a fuzzy laser spot, and such a beam pattern is difficult to read the central position of the spot accurately. By using a circular aperture, the CCD would receive a nearly round spot. So, we can reduce the influence of the turbulence by reshape the laser spot. Secondly, because the experiment needs a long distance of 40 m, it is impossible to complete it on the optical platform in the laboratory. So, the experiment can only be conducted in the corridor and there are many factors that lead to the laser spot shaking such as the walking of people around the equipment and the noise of the large equipment in the lab building.

4 CONCLUSIONS

A subgrade settlement measurement method based on the properties of a laser are presented. Comparing with the traditional methods for measuring subgrade settlement, the laser beam method has the following advantages:

(i) The set up is insensitive to sunlight interference: our charge-coupled device (CCD) system can receive a very bright spot from the focused laser, which makes the system working effectively during daytime with little influence of sunlight even when the distance between laser and CCD is 40 m;

(ii) The cost is relatively low: the equipment used in the experiment consists of a laser, a circular aperture, two lenses, and a CCD;
(iii) The system has a much higher resolution of 0.25 mm when use a lens with focal length of 1000 mm, and the experimental and theory results are agreed almost perfectly with each other; and
(iv) The system is insensitive to the environmental influences such as wind, rain, and sunlight. In this experiment, the location of the laser spot focusing on the CCD is shaking all the time. According to a series of calculations, the atmospheric optical parameters such as atmospheric turbulence influence spot shaking partly.

5 ACKNOWLEDGEMENTS

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