

MEASUREMENT OF LONG FOCAL-LENGTH BASED ON STRIPE MATCHING

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Abstract:

A novel method for accurate long focal-length measurements, based on stripe matching, is proposed. This method consists of a laser source, two gratings and a detector. A divergent beam illuminating two parallel gratings produces moiré fringes on the second grating. Then, added a test lens in front of the first grating, a new moiré fringes is produced. The two moiré fringes are matched by moving the second grating and the corresponding focal-length can be easily obtained by the measurement of the distance between gratings. Experiment demonstrates the proposed method features high accuracy of 0.18% and stability of 0.0004%. Besides, this method tremendously reduces testing time.

Keywords: Long focal-length, Measurement, Stripe matching, Gratings, Moiré fringes

1. INTRODUCTION

It is a great challenge to measure the focal-length of an ultra-long focal-length lens (UFL), which is now widely used in large optical systems, such as space optical system, high energy laser system and laser fusion program. It is of great significance to develop a fast, real-time measurement system to satisfy the stringent requirement for ultra-precision long focal-length measurement. However, it's still very difficult to achieve accurate measurement because that the exact position of the focus is hard to determine and the long measurement light-path can be easily affected by the disturbance of environment [1,2]. Some methods have been proposed in previous literatures to deal with this problem. Meshcheryakov et al.[3] acquired a measured focal-length of 25 m by inserting an optical wedge into the light-path, which changed the position of a luminous slit, achieving an accuracy of 0.1%. Moreover, DeBoo and Sasian [4,5] applied a Fresnel-zone hologram with a precision better than 0.01% when measured a 9 m focal-length lens. This technique worked well when applied to large, slow lenses; but in terms of lenses with large curvature, it is difficult to fabricate suitable hologram and the measurement precision is limited by optical lithography. Besides, W. Zhao et al [1,6] proposed a laser differential confocal technique for long focal-length measurement in 2009. They used a differential confocal focusing system (DCFS) to measure the variation in position of DCFS focus with and without a UFL and then obtain the UFL focal-length from the distance between the two focuses. The precision is about 0.01%, which is depending on the reference lens.

The key for improving the measurement precision is shortening the light path and improving the focusing precision. Those above methods have reached high precision. But the stringent requirement for environmental temperature, air disturbance and vibration are hardly achieved. To

overcome these difficulties, the moiré interferometry method, based on Talbot effect and the moiré technique, have been reported in recent years [7-12]. The research discussed this method in details which employed collimated rays, two equal-period gratings, and the scanning system. The sensitivity of moiré interferometry can be easily tuned by varying the crossed angle between the two gratings, thus high measurement accuracy can be achieved. This method greatly shorten the testing light path, however, in most case the scanning system induced inevitable cumulative errors, making an enormous impact on the accuracy.

In this paper, we propose and demonstrate a novel, feasible and accurate method to overcome these problems. In order to realize full-diameter measurement, we employ divergent beam and two Ronchi gratings of different periods. In this way, the collimation process and scanning system are avoided. The stability and accuracy of the measurement are improved and the time for testing is tremendously reduced accordingly. Furthermore, the whole measurement can be easily achieved through the stripe matching of the moiré patterns, depending on neither precise adjusting mechanism nor troublesome manual adjustment. The experiments confirm the validity and high accuracy of this method.

As follow, the principle of stripe matching and simple description of measurement system will be presented in Section 2; Section 3 provides the experiment process and results; The conclusion will be demonstrated in Section 4.

2. PRINCIPLE

The schematic representation of optical path in our method is shown in Figure (1). We can see from Fig. (1-a) there are two gratings set parallel with each other, we denote the two gratings as G1 and G2. The length of optical path along the optical axis between grating G1 and grating G2 is set as the distance Z , which be referred to as Talbot distance. After pass through grating G1, the monochromatic divergent wave produces a Talbot image G1'. As the wave is divergent, the image G1' is a magnified Talbot image and the period of G1' is expressed as p_1' . Then the Talbot image G1' is superimposed on the second grating G2, creating the image of moiré patterns.

According to the geometrical optics, shown in Fig.(1-a), the focal-length of the divergent wave satisfies the following relation:

$$\frac{f_{wave}}{f_{wave} - Z} = \frac{p_1}{p_1'} \quad (1)$$

Here f_{wave} is negative, regarded as the focal-length of the beams illuminated on the grating G1. The optimal Talbot

distance Z is determined by moving grating G2 along the optic axis.

The tilt angle α between the patterns and the x-axis can be calculated out by computer with the help of Fourier transform algorithm, and the relationship in the image of moiré patterns can be given by

$$\tan \alpha = \frac{\frac{p_2}{p_1'} - \cos \theta}{\sin \theta} \quad (2)$$

In which θ is the crossed angle between two gratings in x-y plane.

Then, as shown in Fig.(1-b), we insert the test lens into the light path in front of the first grating G1 and get a new combined divergent beam. The focal-length of this new beam is called f_{com} . Now the period of the image G' (Talbot image of grating G1) on the second grating G2 is changed. The relationship about the new moiré patterns can be given by

$$\tan \alpha'' = \frac{\frac{p_2}{p_1''} - \cos \theta}{\sin \theta} \quad (3)$$

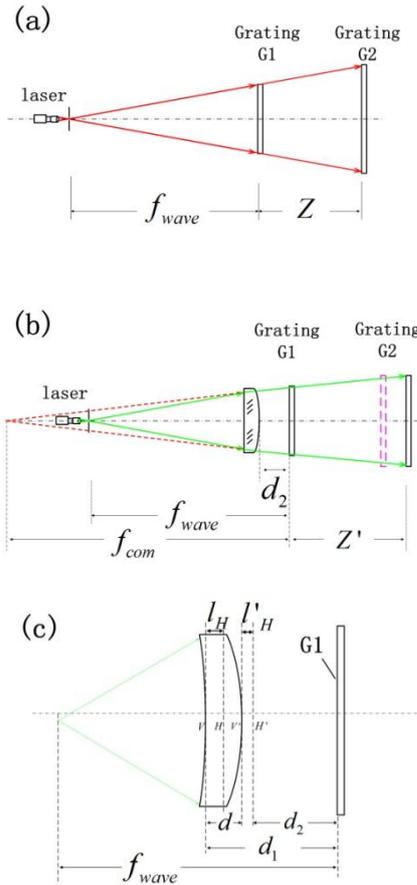


Fig. 1: (color online) Schematic representation of our method. (a) Focal-length of divergent beam, (b) Test lens is inserted, the combined focal-length of new wave is represented as the red dash line. (c) Parameters of test lens

Here α'' is the tilt angle of new patterns, p_1'' is period of new image G1''. This allows us to rewrite Eq. (2) as:

$$\frac{f_{com}}{f_{com} - Z'} = \frac{p_1}{p_1''} \quad (4)$$

In Eq. (4), Z' is the new Talbot distance. Moving the Grating G2 along the z-axis until the α'' is equal to α . According to Eq.(2) and Eq.(4) the period p_1'' is equal to p_1' at this point. Hence we get:

$$f_{com} = \frac{Z'}{Z} f_{wave} \quad (5)$$

The diagram of the lens is shown in Fig. (1-c). The lens parameters are got by the preliminary measurement, the focal-length of the measured lens f_{lens} can be given by:

$$\begin{cases} l_H = \frac{-dr_1}{n(r_2 - r_1) + (n-1)d} \\ l'_H = \frac{-dr_2}{n(r_2 - r_1) + (n-1)d} \\ d_2 = d_1 - d - l'_H \\ f_{lens} = 1 / \left(\frac{1}{f_{com} + d_2} - \frac{1}{f_{wave} + d_1 - l_H} \right) \end{cases} \quad (6)$$

Where, l_H and l'_H indicate the distance between principal plants and surfaces of the lens. r_1 , r_2 and n are radius of two surfaces and refractive index of the lens, respectively. The distance d_1 from front surface of the lens to grating G1 can be measured precisely by grating ruler.

3. EXPERIMENTS AND RESULTS

Figure (2) shows schematic diagram of experiment setup. An infrared laser with wavelength 1053nm is used in our experiment. The parallelity of test lens and two gratings is ensured by an autocollimation. The focal-length of divergent beam is measured by grating ruler with 10um precision, and an electric displacement platform is used to move the grating G2, the precision is also 10um. The accuracy of the inclination angle and the crossed angle, which was discussed in [14, 15], are 0.005° and 0.003° respectively.

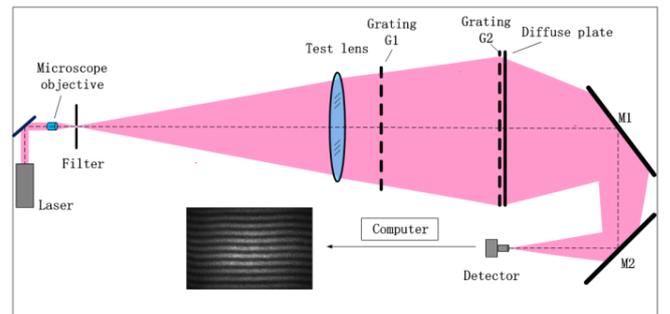


Fig. 2: (color online) Schematic diagram of experiment setup.

The experiment steps are as follow. First we measure the distance between laser and the first grating G1 i.e. the focal-length of divergent beam by a grating ruler. The distance between two gratings is also obtained with the help of the ruler. Tilt angle of the moiré pattern is calculated by computer as α . After that we insert the test lens into the light path and obtain the distance between the lens to grating G1. The corresponding new Talbot distance is determined when the tilt angle of dynamic fringe pattern achieves α (by moving grating G2 with the help of displacement platform). Finally, the focal-length of the lens could be computed out according to Eq. (6).

Table 1 shows the results of the measurement undertaken with 10 lenses of same focal length. To reduce the effect of air turbulence and electronic noise, 10 continuous measurement values are averaged for each measurement point. Comparing experiment results with the nominal values, the relative error $\Delta f / f$ of the measurement of focal-length of lenses is better than 0.36%. Hence, the measured focal-length of the lenses agrees well with the nominal values.

Table 1: Comparison between nominal values and experiment results.

No.	Nominal $f(mm)$	Measured $f(mm)$	$\Delta f(mm)$	$\Delta f / f \times 100$ (%)
1	13500	13498.7	-1.3	-0.009
2	13500	13485	-15	-0.111
3	13500	13479.3	-20.7	-0.153
4	13500	13489.5	-10.5	-0.077
5	13500	13492.5	-7.5	-0.055
6	13500	13468.4	-31.6	-0.234
7	13500	13450.6	-49.4	-0.365
8	13500	13488.3	-11.7	-0.086
9	13500	13487.9	-12.1	-0.089
10	13500	13498.4	-1.6	-0.011

Further experiments are performed to verify the new method works with high accuracy. The lenses we test above are also measured by the knife-edge test and Hartmann approach. Because of experimental conditions, only 3 pieces lenses are tested by Hartmann approach. And different wavelength beam are employed in different approaches, hence the nominal values of these lenses are different (13192mm in knife-edge test and 13452mm in Hartmann approach). Table.2 shows the measurement results of knife-edge test and Hartmann approach and Fig.(3) shows the relative errors of each approach. The blue, red and green curves represent the relative error of the knife-edge test, Hartmann approach and our system, respectively. Comparison between these three systems are demonstrated in Fig.(4). Good agreement can be seen from the two figures. The relative error between three systems in Fig. (4) is better than 0.18%, indicating the high relative precision of our system. Comparison of these systems reveals that the long

Table 2: Measurement results of knife-edge test and Hartmann approach.

No.	Knife-edge (mm)	Error (%)	Hartmann (mm)	Error (%)
1	13192	0	-	-
2	13179	-0.098	-	-
3	13195	0.022	-	-
4	13197	0.037	-	-
5	13191	-0.007	13453	0.01
6	13169	-0.174	13426	-0.19
7	13156	-0.272	13409	-0.32
8	13167	-0.189	-	-
9	13177	-0.113	-	-
10	13156	-0.272	-	-

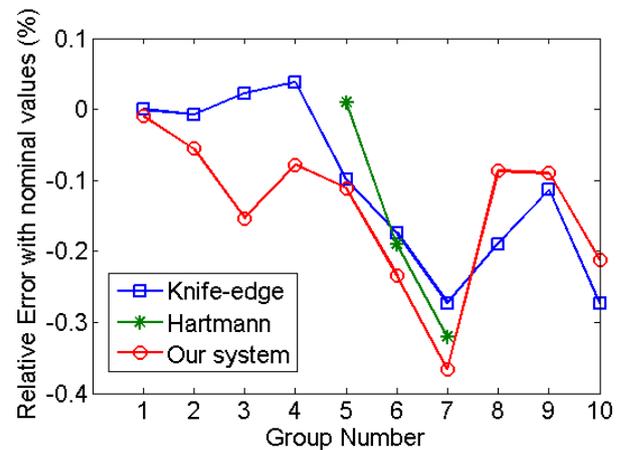


Fig. 3: (color online) Results of three approaches. The blue, red and green curves represent the relative error of the knife-edge test, Hartmann approach and our system, respectively.

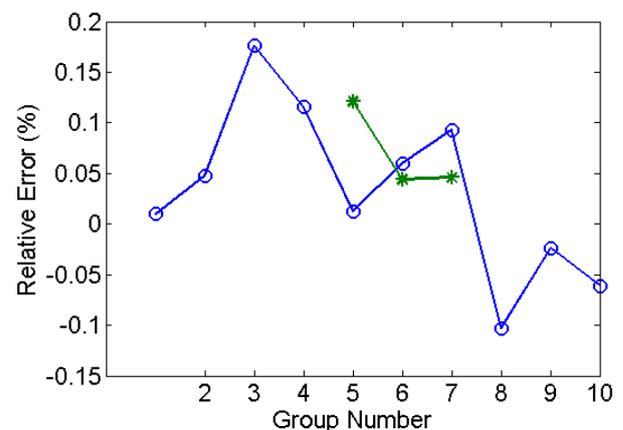


Fig. 4: (color online) Results for comparison. The blue curve represents the relative error between knife-edge test and our system, and the green curve represents the relative error between Hartmann approach and our system.

focal-length can be measured accurately by using the proposed method.

The stability is also important for a precision measurement system. To check it out, some other independent measurements are carried out. A 13500mm focal-length lens is fixed in our system for 24 hours. As shown in Fig. (4), 20-groups measurements with time interval of one hour are demonstrated. Each spot in Fig.(4) denotes the average values of 10 continuous measurements within each group. The standard deviation of those measurements values is 0.0557mm, better than 0.0004%. It is clearly that our system is of high accuracy and insensitive to the testing environment. Both the sound validity and stability of the proposed new method can be told obviously.

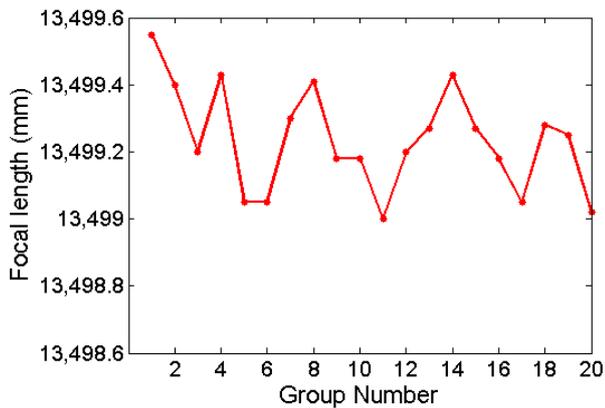


Fig. 4: (color online) Results for stability experiment.

4. CONCLUSION

A novel method of long focal-length measurement based on stripe matching is proposed. In this method, a divergent beam illuminating two parallel gratings produces moiré fringes on the second grating. Then, added a test lens in front of the first grating, a new moiré fringes is produced. The two moiré fringes are matched by moving the second grating and the corresponding focal-length can be easily obtained by the measurement of the distance between gratings. In the experiments, the novel method shows good performance in testing accuracy, and both the sound validity and stability of the proposed new method can be told obviously.

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