

Application of Adaptive Optics for Flow Visualization in Open-Air



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Abstract Objective of this research is high spatial resolution acquisition of measurement image in telescopic visualization measurement. Telescopic visualization measurements cannot be performed under strong atmospheric disturbances because of the spatial resolution degraded. So that, an adaptive optics system combining a deformable mirror and a wavefront sensor is used to reduce the influence of atmospheric disturbance. The visualization measurement uses a background-oriented schlieren method that has attracted attention for use in open-air. In this paper, the phase plate was used to conduct the experiment indoors. The phase plate was designed and manufactured from the result of measuring the atmospheric disturbance. In addition, the phase plate was combined into the adaptive optics system and experiments were performed.

Keywords Background-oriented schlieren · Deformable mirror · Wavefront sensor

1 Introduction

Recently, by the increase of global air demand, optimization of arrival and departure intervals at airports is required. At Tokyo International Airport (Haneda Airport) the aim is to increase the number of arrivals and departures. The cause of the time separation between aircrafts is the wake turbulence of the aircraft. For example, according to International Civil Aviation Organization (ICAO) regulations, a small

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aircraft following a large aircraft requires a time separation of 159 s. Therefore, the time interval can be optimized if the developmental aspect of the wake turbulence of the aircraft can be visualization measured with high spatial resolution, and the optimization of the departure and arrival intervals can be expected. Recently, for research purpose, the LIDAR has been used to detect the turbulence caused by a large aircraft at take-off and landing at a few airports. Spatial resolution of the LIDAR is about 30 m at most. Thus, authors initiated the research for precise detection of the wake turbulence by optical flow visualization method, background-oriented schlieren (BOS) [3]. On the other hand, under the strong atmospheric disturbances such as at an airport, spatial resolution decreases due to atmospheric disturbances, especially for telescopic imaging. In this research, a deformable mirror and a wavefront sensor were installed in optics of BOS to improve the images taken under strong atmospheric disturbances. In this report, a phase plate, which is a thick resin disk with a density gradient, was designed to simulate atmospheric turbulence for an experiment in laboratory. The phase plate was evaluated by measuring laser beam scintillation whether atmospheric turbulence was reproduced.

2 Methodology

2.1 Adaptive Optics

The concept of adaptive optics [6, 7] was proposed in 1953 for astronomer Babcock to achieve the diffraction-limited angular resolution of terrestrial telescopes. Figure 1 shows that schematic of adaptive optics . Adaptive optics is a technique to correct the light wavefront that is disturbed by disturbance. A wavefront sensor (WFS) and a deformable mirror are used to correct the light wavefront shape affected by atmospheric disturbances. Wavefront correction is performed by repeatedly performing control to feedback information obtained by the wavefront sensor to the deformable mirror (DM). The wavefront sensor is a device for measuring the phase plane of light and reconstructs the wavefront from the information obtained from the wavefront sensor using Zernike polynomial. Here, it uses the Shack–Hartmann wavefront sensor. The Shack–Hartmann wavefront sensor has a microlens array in front of the sensor. The wavefront is divided by the microlens array, and the inclination of the wavefront is obtained from the movement amount of the focal point in each lens. The deformable mirror can deform the shape of the surface and perform wavefront correction by deforming the mirror so that the wavefront error of the distorted wavefront becomes smaller when reflected by the deformable mirror. Here, it uses a MEMS deformable mirror that deforms a mirror by electrostatic force in a method using microelectromechanical systems (MEMS) technology.

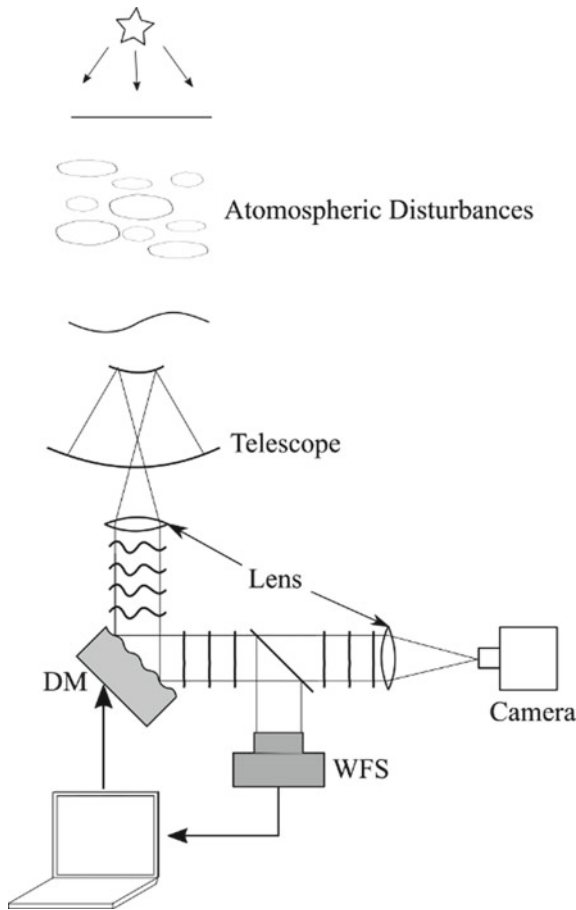


Fig. 1 Schematic of adaptive optics: wavefront sensor, deformable mirror

2.2 Background-Oriented Schlieren Method

Background-oriented schlieren (BOS) method [3, 3] was presented at a conference in 1998 and was registered as a patent in 1999 by Meier, a member of the Deutsches Zentrum für Luft- und Raumfahrt e.V. Figure 2 shows that schematic of BOS. The background-oriented schlieren method is a visualization method that records the refractive index distribution in the flow field as the distribution of the amount of movement of the background placed behind the phenomenon. For this reason, the background pattern is often used to analyze the movement of the background, and in many cases, random dot patterns are used. For recording the phenomenon, take one set of images for each measurement. One is an image in anticipation of the measurement part in the reference state where no phenomenon occurs. The other is an image in anticipation of the phenomenon. Each of these is called a reference

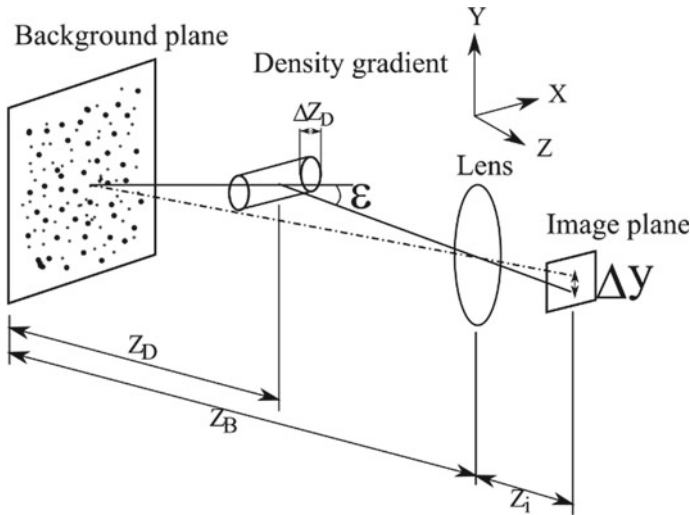


Fig. 2 Schematic of principle of background-oriented schlieren

image and a measurement image. An angle of refraction is given to the light beam by the refractive index gradient in the phenomenon passing from the background to the image recording element, and a small amount of movement is observed in part of the background image. This refraction angle is estimated from the amount of movement of the background image, and the density distribution is reconstructed. To obtain the refraction angle ϵ from the amount of background movement, assuming that the paraxial optical system and the declination are small, the amount of background movement Δy on the image recording element can be expressed as Eq. (1) by the phenomenon.

$$\Delta y = Z_D \cdot M \cdot \epsilon \tag{1}$$

$$M = Z_i / Z_D \tag{2}$$

Here, the background-phenomenon distance Z_D , the background-lens distance Z_B , the focal length Z_i of the imaging lens, and the magnification of the optical system M . In addition, ϵ can be expressed as Eq. (3) if the refractive index n_0 of the initial state of the medium, the refractive index change n due to the phenomenon, and the depth ΔZ_D in the direction of the line of sight of the phenomenon.

$$\epsilon = \frac{1}{n_0} \int_{Z_D - \Delta Z_D}^{Z_D + \Delta Z_D} \frac{\delta n}{\delta y} dz \tag{3}$$

Furthermore, given the density ρ of the medium, the refractive index n , and the Gladstoe–Dale constant K , it is possible to relate Δy to the density gradient generated by the phenomenon from (4) of Gladstoe–Dale equation.

$$n = K \cdot \rho + 1 \quad (4)$$

3 Experimental Setup

Figure 3 shows that schematic of the optical system used in this experiment. Beam diameter of 4.4 mm was formed when light was incident on a beam expander consisting of lenses **L1** ($\phi = 25.4$ mm, $f = 150$ mm) and **L2** ($\phi = 25.4$ mm, $f = 25.4$ mm). The phase of the wavefront was disturbed by the light incident on the phase plate. This makes it possible to simulate the effects of atmospheric disturbances indoors as well. The light reflected by the deformable mirror (THORLABS, MEMS type, Actuator Array 14×14 , Clear Aperture 4.4×4.4 mm) was split by a beam splitter into a wavefront sensor (THORLABS, 1440×1080 pixel, Microlens Arrays 47×35) and a camera (Allied Vision, 1280×1024 pixel, 168 fps) for measurement. The phase plate had a phase distribution as shown in Fig. 4. White was a positive phase and black was a negative phase. The phase of incident light can be disturbed by rotating the phase plate. In this experiment, laser (THORLABS, CPS635R, 635 nm) was targeted for wavefront correction. It corrects the wavefront that has passed through the phase plate.

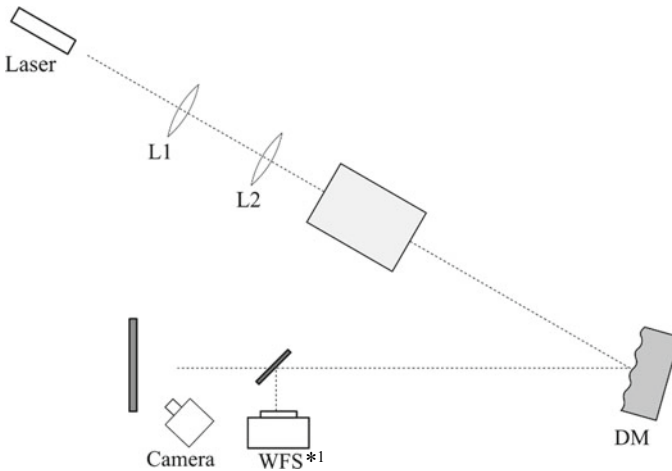


Fig. 3 Schematic of experimental optical system: *¹Wavefront sensor; *²Deformable mirror

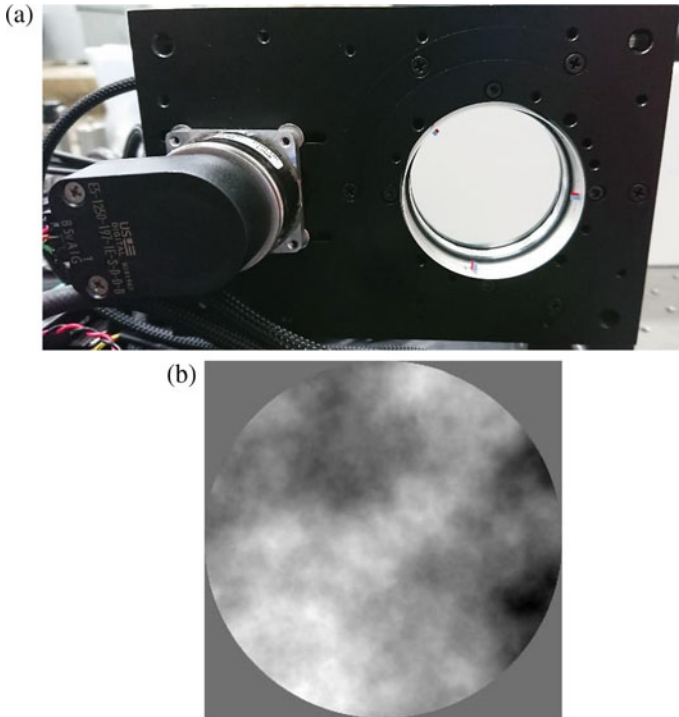


Fig. 4 a Phase plate device; b Phase pattern

4 Results

The atmospheric disturbance was measured when manufactured the phase plate. The freed length was measured as 5 mm. So that the phase plate manufactured to freed length 5 mm. The freed length can make constant by changing the number of rotations according to the size and position of the beam. The phase plate was combined into the optical system to perform a wavefront correction using a laser. As a result, when a deformable mirror and a wavefront sensor were combined, the light intensity of the laser increased. Therefore, a wavefront correction was confirmed by the deformable mirror and wavefront sensor.

5 Conclusions

The purpose of this research is to make a visualization measurement under strong atmospheric disturbances near the ground. To confirm that it is possible to remove the influence of atmospheric disturbances using existing adaptive optics. In this paper,

the phase plate was designed and manufactured from the result of measuring the atmospheric disturbance. An experiment was carried out by combining the phase plate into the adaptive optics system. The result is:

- We manufactured the phase plate with a focal length (r_0) 5 mm from the results measurement of atmospheric disturbance.
- The phase plate was combined into an adaptive optics system and the experimental conditions were $r_0 = 5$ mm.
- A telescope with an effective diameter 203 mm attaches to the optical system, and telescopic measurements are planned open-air.

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