Visualization of Vortices Generated by Flapping Wing Device by Schlieren Method

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Abstract. Visualization and measurement of airflow detail structures is a difficult problem. In the past few years, high-speed DPIV has been used to capture the vortex structures on flapping robotic insect wings. Due to the inherent limitation in DPIV technique, important airflow activity in small scale vortical flow structures may be missed. In this paper, high-speed Schlieren photography was applied to vortical flow Visualization on a flapping robotic insect wings and then provided more information of vortical flow structures in detail. Based on the Schlieren image, quantified velocity vectors field was obtained by applying the variational optical flow method, which is able to be extending the potential applications to development flapping wings aircraft.

1. Introduction

Insects have mastered excellent flying skills during a long evolutionary process. For example, bees use vortex suction for highly maneuverable flight, and their flapping movements are very complex, and they can flexibly generate, maintain, strengthen and use vortices [1]. Insects like fly, bee and dragonfly can use the vortex generated by the flapping wing movement to make hovering, inverted flight, acceleration, deceleration, dive, jump, rotation and other extremely efficient flying actions in the air. [2-3]

In view of the skills and efficiency of insects in flight, the aerodynamic characteristics of insect flight have very important reference significance in the research of miniature flapping wing aircraft in the field of bionics. The development of miniature flapping wing aircraft is closely related to the study of insect flight mechanisms. It involves the in-depth development and cross-application of disciplines and technology including bionics, aerodynamics, MEMS [4] technology, micro-design, micro-manufacture and micro-control, etc., which is a boom in bionic research at home and abroad in recent years. It has received attention in the military and civilian fields.

In order to study the aerodynamic characteristics of flapping wings, airflow visualization technique is needed to measuring flow field physical parameters, observing and analyzing the corresponding flow field structure. In recent years, researchers have applied PIV technique to aerodynamic performance research of micro flapping aircraft [5]. However, it is difficult for PIV to provide abundant flow field details, which may result the important characteristics of the micro-flapping-wing aircraft be ignored [6-7]. In contrast, schlieren method, as a non-contact airflow field visualization technique, is able to convert a change in refractive index in the air into a change in light intensity, thereby reflecting the distribution of density in the air. It can measure a large amount of airflow field data at a lower cost and get richer details of the airflow field. [8-12]
Therefore, this paper applied schlieren method to the airflow visualization and further research of the Flapping Robotic Insect Wings.

2. Methods and Material

2.1. Flapping wing vortex generator
In this paper, a simulation device of flapping wing aircraft is made as a vortex generator. By controlling the three-dimensional rotation parameters of flapping wings, various types of vortices with different physical properties are manufactured for research.

2.2. Schlieren airflow visualization device

2.2.1. Schlieren principle. The change in the density of the gas flow field has a linear relationship with the refractive index of the gas, that is, \( n-1=Kcn\,\rho \), where \( n \) is the refractive index of the gas, \( \rho \) is the density of the gas, \( Kcn \) is Gladstone-Dale constant. If there is a change in the refractive index gradient in the direction perpendicular to the light, the deflections of adjacent lights are different, so these lights will be converged or diverged, causing the imaging illuminance to increase or decrease. These changes in illuminance can be filmed and observed by the camera.

2.2.2. Schlieren system design. The schlieren system includes a light source, a schlieren mirror, a knife-edge mechanism, an imaging component, or a camera.

In order to obtain a complete image of the vortex generated by the flapping device until it dissipates, a sufficient range of field of view is required to ensure that the movement and change of the vortex can be observed. Because of the difficulty in designing aberrations of large-aperture lenses and ensuring high quality inside glass materials, spherical lenses or parabolic mirrors can be used to replace the lenses in general to form a large-field-of-view mirror optical system. Not only does it meet the requirements of a large field of view, but the structure inside the glass will not affect the reflection effect of the mirror surface, and the reflection of the mirror will not produce chromatic aberration.

Traditional superimposed schlieren optical system, which allows the schlieren light path to pass through the test area twice. The deflection angle from the light source is increased, and the schlieren sensitivity is twice that of a single pass. This system is more suitable for observing weak disturbances. In addition, due to the spatial characteristics of the gas vortex, it is necessary to establish an optical system for multi-dimensional observation. Compared with other coincident schlieren optical systems, the system has a simpler structure. Using a beam splitter can not only effectively eliminate double images, but also flexible adjustment of the position and angle of light focus makes it easier to design the optical path of the multi-dimensional schlieren optical system.

To sum up, this article chooses to use a parabolic mirror with a diameter of 200mm and a focal length of 800mm as the reflector, and uses a beam splitter to eliminate double images.

2.2.3. Choice of light source. The light source is the signal input of the schlieren system, which affects the observation of the entire system and the calculation accuracy of the schlieren algorithm. The luminous source of the schlieren system generally uses a laser light source or an LED light source. Due to the strong coherence of the laser light source, it is easy to cause diffraction effects and affect the imaging effect. The LED light source does not have coherence, the wavelength range is narrow, the imaging quality is more uniform, and approximating the light source can also provide the brightness required for shooting at 1000fps, while using monochromatic light can avoid dispersion. In addition to the optical properties of LED light sources, due to their size is much smaller than other light sources, it is more flexible for more complex light path designs, which is beneficial to avoid the effects of occlusion and overlap between light paths.

Moreover, the calculation formula is based on the illuminance:
Where $I_0$ is the illuminance, $B$ is the brightness, $b$ is the width of the light source, $m$ is the magnification of the concave lens and the camera objective lens, and $f$ is the focal length.

At the same time, the illuminance of the camera is also proportionally increased as the area of the light source increases. In order to achieve uniform illumination, a diaphragm needs to be set at an effective light source position.

To sum up, this article chooses a monochromatic LED light emitting chip as the divergent light source, and uses a diaphragm to reduce the area of the light source. And the small hole diameter is less than 0.9mm.

2.2.4. Choice of knife edge. In the schlieren system, the role of the knife edge is critical, and light will deflect after passing through an inhomogeneous medium. The role of the knife edge component is to perform optical spatial filtering at the focal position, blocking out part of the deviation Light. At the same time, according to the calculation relationship of the sensitivity of the schlieren system:

$$R_E = \frac{f}{s_k}$$  \hspace{1cm} (2)

$R_E$ is the relative degree, $\alpha$ is the deflection angle, $f$ is the focal length of the single optical path, and $s_k$ is the height of the unblocked light spot.

Using formula (2), the sensitivity of the schlieren system can be measured.

Namely, the sensitivity of the schlieren system is directly related to the focal length of the schlieren mirror and the size of the cutting edge cutting light source. The greater the focal length of the schlieren mirror, the larger the light source part blocked by the knife edge, the higher the sensitivity of the schlieren system.

In addition to the size of the knife-edge cutting light source, the thickness of the cutting edge also has a significant effect on the schlieren image. The increase in the thickness of the cutting edge can be equivalent to the increase of the knife-edge height [13].

In summary, the knife edge should be adjusted experimentally, and the sensitivity of the schlieren device should be calculated to find the sensitivity and illuminance of the schlieren image which are compatible with the system. Moreover, in order to reduce the thickness of the knife edge, an iron blade was immersed in hydrochloric acid by using a corrosion method to reduce the thickness of the blade, and the thickness of the knife edge was less than 0.1 mm.

2.2.5. Choice of camera. The research object selected in this article is a small-scale vortex with a motion cycle of 1 to 2 seconds. The vortex movement needs to be imaged in a very short time. This paper uses a high-speed camera of 1000 fps and 640*480 pixels as the camera system Continuous imaging of the entire cycle of the vortex.

2.2.6. Device parameter optimization. We put the flapping wing device in the observation area, brush the alcohol on the surface of the wing, and then control the Microprogrammed Control Unit to make the flapping flap, so that the small-scale vortex (wingtip vortex) can be clearly observed through the schlieren. We investigated the size, period, and denseness of the vortex.

3. Results

This paper studies vortices based on the schlieren method. Since the high-speed-dual-path speckle method is used in this paper, this method is more sensitive to changes in the flow field gradient information, so it is more suitable to observe the changes of the vortex. The video captured by the high-speed camera here will be specifically quantified by software developed based on matrix operations, making the quantization process relatively simple. Fig 1 shows the schlieren pattern of the air around
the flapping wing. It can be seen that when flapping wing device vibrates at high speed, vortex will be generated behind it.

![Figure 1. The schlieren pattern of the air around the flapping wing](image)

3.1. Measurement of gas vortex velocity field.
Quantified velocity vectors field was obtained by applying the variational optical flow method. Because the algorithm steps involve the selection of three hyperparameters, the loop-traversal method is combined with the ideal-principal component analysis method to select the optimal parameters. Namely, the optimal parameter selection makes the stability score of $\alpha, \beta, \lambda$ of the velocity field formula the highest. [14-15]

3.2. Analysis of vortex developing.
The process of vortex generation, movement, and dissipation and its data characteristics are now studied. From the left to the right, the density, velocity and vorticity fields of the vortex are shown in Fig2.

![Figure 2. The density, velocity and vorticity fields of the vortex](image)

The generation period of the vortex is the stage just when the flap wing flaps downwards. During it flaps downward, the relative speed between the edge and the air is low, and the air viscosity is relatively large relative to its own inertia, which makes the Reynolds coefficient low. It creates vortices. Vortex at this stage, because the boundary layer has just formed, generates external shear forces, and acts as a squeezing action on the inner air, making its core density denser than the surroundings, but its range of influence is small at this stage, and the velocity field reflects. The boundary layer proves that there is a shearing force. The vorticity field shows that there is a shearing force at the boundary. However, it was just after the vortex was generated, its vortex structure was not stable, and the vorticity at the corresponding position was low.

The vortex in the movement period has formed a stable structure. The continuous action of the wing edges and air provides energy for the vortex. We can still see that there is a shear force in the vortex boundary layer. The air inside the vortex is squeezed in a larger range during the generation period, and the internal speed of the vortex is the combined velocity under the combined effect of the speed of rotation, the speed of air expansion, and the speed of the overall deviation from the vortex. The
generation period is wide and large, which indicates that the vortex has gradually stabilized its structure at this stage.

During the dissipation period of the vortex, as the flapping wing movement speed has slowed down or is zero, its vortex structure begins to become unstable due to the weakening of the energy provided. We can observe its density map. The density inside the vortex has become smaller than the other two stages and the density distribution in the same range is more uniform. From the velocity field, it can be seen that the original shear force is weakened. The squeezed air started to spread making the vortex expand more than other stages. From the vorticity diagram, the distribution is not concentrated in the first two periods and the vorticity is decreasing, which again proves that its vortex structure is gradually unstable and dispersed.

4. Conclusion

In fact, when air flows around an object, vortices that alternately fall off appear on the back and sides of the object to form a Karman vortex. The faster the airflow flows, the faster the formation speed. If the airflow velocity is not equal, the flow velocity is large. A strong vortex is formed on the side with a large flow velocity, namely, a leading edge vortex. In the process of flapping the wings in one cycle, the wingtip vortex trail is more obvious, at the place where it is formed, the displacement is small. With the flapping of the wing, the displacement of the wingtip vortex is small, but the gray scale becomes smaller when the wingtip vortex is formed, which indicates that the wingtip vortex is spreading.

The purpose of this study is to explore the potential value of the schlieren method in the aerodynamic performance research and optimization design of flapping-wing aircraft, and to quantify the physical field, and to explore a variety of optical flow method calculation models that are more suitable for the schlieren system. It has practical significance in the expansion of the schlieren method, the visualization of gas vortexes, the study of insect flight mechanisms, and the development of flapping wing aircraft, and it is worth actively exploring.

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