Optical Measurement of the Deformation, Motion, and Generated Force of the Wings of a Moth, *Mythimna Separata* (Walker)*

Shigeru SUNADA**, Deqiang SONG***, Xiannan MENG***, Hao WANG***, Lijiang ZENG*** and Keiji KAWACHI****

Motion and deformation of the wings of a moth *Mythimna Separata* (Walker) tethered to a steel beam were measured by using an optical method that uses fringe pattern projection. Simultaneously, the vertical force due to aerodynamic force generated by the wings was estimated by measuring the bending deformation of the beam during flapping motion of the moth. The force was estimated by subtracting the vertical forces due to inertial and centrifugal forces acting on the wings, which were estimated from the measured flapping motion, from the measured vertical force. Both the measured motion and deformation of the wing and the estimated vertical aerodynamic force generated by the wings suggest that the feathering angles are mainly affected by the inertial moment generated by the flapping motion and that the wing camber is mainly affected by the aerodynamic force generated by the wing.

**Key Words:** Optical Measurement, Moth Wings, Vertical Aerodynamic Force, Deformation of a Wing

1. Introduction

Recently, the mechanism of aerodynamic force generation by insect wings has gained interest because a micro air vehicle with flapping wings is being developed under DARPA MAV program. Aerodynamic force generated by insect wings depends on the motion and deformation of the wings, and accurate measurements of the motion, deformation, and generated force of the wings will be needed for further research of insect flights. The force generated by insect wings has been measured with high accuracy by using a force probe and by an optical method. These methods can measure the aerodynamic force but not the motion and deformation of insect wings.

The wing motion has been determined as variations of the flapping angle and feathering angle observed in images taken by a high-speed camera or a high-speed video camera. However, the detailed deformation of wings including camber change cannot be determined from these images with high accuracy. This is a drawback in the previous methods for analyzing insect flights, because wing characteristics strongly depend on camber. In addition, measuring camber change together with variation of feathering angle is important to investigate the functional principle underlying wing design that camber in some insects can be automatically varied with torsion, that is variation of feathering angle.

In our study, we measured the flapping and feathering angles of a tethered moth and the deformation of its wings by using an optical method developed by Song et al. that uses fringe pattern projection. Simultaneously, we used a laser to measure the bending deformation of the steel beam to which the moth was tethered. The vertical force generated by the wings was estimated from the measured bending deformation of the beam. This vertical force is com-
posed of the aerodynamic force generated by the wings and the inertial and centrifugal forces acting on the wings. These inertial and centrifugal forces were estimated from the measured flapping angle. The vertical force due to the aerodynamic force generated by the wings was estimated by subtracting the calculated vertical force due to the inertial and centrifugal forces from the measured vertical force.

This method can measure the motion, deformation, and generated force of insect wings with high accuracy. However, wing motion during tethered flight might show characteristics not seen during free flight. Therefore, results obtained by this method will be useful for investigating relations among the motion, deformation, and generated force of insect wings.

2. Methods

A moth *Mythimna Separata* (Walker) was tethered with adhesive at the head to the beam as shown in Fig. 1. Table 1 shows the morphological data for the tested moth. The optical system that we used in the measurements consists of two parts: one to measure the wing deformation together with the flapping and feathering angles at 25%, 50%, and 75% span-wise positions, and the other to measure the vertical force generated by wings.

2.1 Flapping angle, feathering angle and camber

The wing deformation was measured by using a fringe pattern projection method. A fringe pattern projector (FPP) that consists of a semiconductor laser and a grating was used to generate sharp comb-fringes with an interbeam angle of 0.38 deg. Images of the distorted fringes were then obtained by using a high-speed camera (Dalsa D556) at 955 frames per one second. A representative captured image is shown in Fig. 2(a). The 3D coordinate of any point on the distorted fringes can be calculated by triangulation\(^{(13)-(10)}\), and that of any point outside the pattern of the fringes can be calculated by linear interpolation. We confirmed the accuracy of the measurement system by measuring a half-round surface with a radius of 19.00 mm. Using this real curve as a reference, the measurement results had a standard deviation of 0.10 mm. The accuracy is mainly limited by the number of pixel of the image. We reconstructed the wing shape by using the 3D coordinates as shown in Fig. 2(b). The flapping angle, feathering angle, and wing deformation were determined directly from the images. As shown in Fig. 3, the flapping angle \(\phi\) and feathering angle \(\alpha\) are defined as follows. First, we define the

Table 1 Morphological data for the tested moth, *Mythimna Separata* (Walker)

<table>
<thead>
<tr>
<th>Item</th>
<th>Abbreviation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass of the moth</td>
<td>(m_t)</td>
<td>0.13g</td>
</tr>
<tr>
<td>Wing mass of left forewing and hindwing</td>
<td>(m_w)</td>
<td>0.002g</td>
</tr>
<tr>
<td>Wing length of a forewing</td>
<td>(l)</td>
<td>18mm</td>
</tr>
<tr>
<td>Beating frequency</td>
<td>(f)</td>
<td>35Hz</td>
</tr>
</tbody>
</table>

![Fig. 1](image1) Configuration of the system used to measure the deformation, motion, and generated forces of the wings of a moth

![Fig. 2](image2) Measurement of flapping wings

(a) Image of wings with distorted fringe

(b) Reconstructed wing shape

*JSME International Journal*
Fig. 4 Forces and moments acting on the moth body

line between the root and tip of the forewing, and is approximately on the stroke plane. The flapping angle $\phi$ is the angle between the $x$ axis and the horizontal line as shown in Fig. 3(a). Secondly, we define a plane $\sigma$ at $x = kx_w$ (where, $0 \leq k \leq 1$, and $x_w$ is the length of the forewing) as a plane perpendicular to the $x$ axis and includes point $P$ ($x = kx_w$) on the $x$ axis as shown in Fig. 3(b). Thirdly, we define a wing section as a section where plane $\sigma$ and the wing intersect. Line $AB$ is a line between the leading and trailing edges of the wing section as shown in Fig. 3(c), and corresponds to the $y$ axis. The $z$ axis together with $x$ and $y$ axes make a right-hand coordinate system. Finally, we define the feathering angle $\alpha$ at $x = kx_w$ as the angle between line $AB$ ($y$ axis) and the stroke plane as shown in Fig. 3(c).

2.2 Vertical force

Concurrently with the measurement of vertical force generated by the wings we measured the bending deformation of the steel beam (Young's modulus $E = 2 \times 10^{11}$ N/m$^2$) by using a laser. The beam was 30 mm long and had a rectangular cross-section whose width was $a = 2$ mm and height was $b = 1.6$ mm. By applying an impulse force to the beam, we measured the natural frequency of the beam in air, about $10^5$ Hz. This natural frequency is significantly larger than the beating frequency of the moth ($f = 35$ Hz). Therefore, when the bending deformation of the beam due to an applied force was known, the value of the applied force was estimated as follows:

First, the bending deformation $\delta$ of the beam at point $Q$ was measured by using a laser as shown in Fig. 4. Note that the $\delta = 0$ when the moth was not flapping its wings. The force $F$ and moment $M$ are exerted by the moth on the beam at point $R$ and thus cause the beam to bend.

When a force $F$ and a moment $M$ were applied at point $R$, bending deformation $\delta$ at point $Q$ was calculated as follows:

JSME International Journal
\[ \delta = \frac{I^2}{6EI}(F(3h_i - s_i) - 3M), \]  
where \( I \) is the second moment of area of the beam and is \( I = \frac{ab^4}{12} \approx 6.8 \times 10^{-3} \text{ m}^4 \).

Referring to Fig. 4, the equation of motion for the center of gravity of the body (i.e., head, thorax, and abdomen) along the \( Z \) axis (vertical axis) is given by
\[ (m_{tot} - 2m_w)\ddot{Z} = F_i + F_c + F_a - F, \]  
where \( m_{tot} \) is the total mass of the moth, \( m_w \) is the mass of the left forewing and hindwing, \( m_{tot} - 2m_w \) is the mass of body, and \( F_i, F_c, F_a \) are vertical forces due to inertial force acting on the wings, due to the centrifugal force acting on the wings, and due to the aerodynamic force generated by the wings, respectively. The rotation motion around the center of gravity of the body (i.e., head, thorax, and abdomen) is given by
\[ I\ddot{\Theta} = M_0 - M - FL, \]  
where \( I \) and \( \Theta \) are moment of inertia of the body and inclination of the body, respectively. And \( M_0 \) is a moment which the wings exert on the body and \( M \) is a moment which the beam exerts on the body. In the measurements, the time-variations of \( Z \) and \( \Theta \) are so small that \((m_{tot} - 2m_w)\ddot{Z} \) and \( I\ddot{\Theta} \) can be neglected in Eqs. (2) and (3). Then, from these equations,
\[ F = F_i + F_c + F_a, \]  
\[ M = M_0 - FL. \]  
Substituting Eqs. (4) and (5) into Eq. (1),
\[ \delta = \frac{I^2}{6EI}(F(3h_i - s_i + 3L) - 3M_0). \]  
The moment \( M_0 \) is caused by aerodynamic, inertial and centrifugal forces acting on the wings. The distance in the \( X-Z \) plane between the pressure center of the wings and the center of gravity of the body and that between the center of gravity of the wings and the center of the gravity of the body can be assumed to be about 0.2c \( \approx 1 \text{ mm} \) (c : averaged chord length of the wings). Then,
\[ M_0 = 0.2cF. \]  
Substituting Eq. (7) into Eq. (6),
\[ \delta \approx \frac{I^2}{6EI}(F(3h_i - s_i + 3L - 0.6c)). \]  
From Eq. (8),
\[ F \approx \frac{1.6 \times 10^4}{I^2(3h_i - s_i + 3L - 0.6c)} \]  
where, \( h_i \approx 29 \text{ mm}, s_i = 27.5 \text{ mm}, L = 3 \text{ mm} \) and \( c \approx 5 \text{ mm} \). By using this equation, the value of \( F \) can be obtained from the measured value of \( \delta \).

The forces, \( F_i \) and \( F_c \), were estimated by using the measured wing motion as follows. When the center of gravity of the wings is assumed to be located at the half span-wise position, vertical force due to the inertial force acting on wings \( F_i \) and vertical force due to the centrifugal force acting on the wings \( F_c \) can be expressed as
\[ F_i = 0.5x_w m_w \dot{\phi} \cos \phi \sin i, \]
\[ F_c = 0.5x_w m_w \dot{\phi} \sin \phi \sin i, \]  
where \( i \) is the angle between the stroke plane and horizontal plane. The uncertainty of the force measurement is about 0.1 mN, depending on the stability of the laser measurement system.

### 3. Results and Discussion

The inclination of the stroke plane \( i \) was about 90 deg. Figure 5 shows the time-variations of the measured flapping and feathering angle at 25%, 50% and 75% span-wise positions. The flapping angle could be measured during the entire flapping cycle, whereas the feathering angle could not near pronation. Near pronation, the wings clapped overhead and they are almost parallel to the direction of the semiconductor laser. No fringes can be seen on the wing. Therefore, the feathering angle and wing deformation can be measured during only part of the flapping cycle.

The amplitude of the flapping angle was about 125 deg. Here, the period when the flapping angle was a constant (23 ms < t < 27 ms; \( t \) is time) was included in the upstroke. The feathering angles at 25%, 50% and 75% span-wise positions were nearly the same during the latter half of the downstroke. During this period, the feathering angle decreased. In contrast, during the first half of the upstroke, the feathering angle increased as the span-wise position for the feathering angle approached the wing tip, and the feathering angle increased as the flapping angle increased.

Figure 6 shows the measured chord-wise deformation of the wing at the 50% span-wise position. Figure 7 shows the measured time-variation of the maximum camber at the 25%, 50% and 75% span-wise positions. Maximum camber at the 50% span-wise position in Fig. 6 corresponds to the value of \( z \) for maximum \( |z| \) in Fig. 6. The \( z \) axis is the vertical axis in the insets in Fig. 6 and the \( x-y-z \) coordinate
Chord-wise deformation of the wing at 50% span-wise position. Insets in the figures show the cross-sectional shape of the wing in millimeters. The vertical axis is $z$ axis and the direction of horizontal axis is in accordance with that of $-y$ axis.

![Figure 6](image)

Fig. 6 Chord-wise deformation of the wing at 50% span-wise position. Insets in the figures show the cross-sectional shape of the wing in millimeters. The vertical axis is $z$ axis and the direction of horizontal axis is in accordance with that of $-y$ axis.

![Figure 7](image)

Fig. 7 Time-variations of maximum camber at 25, 50 and 75% span-wise positions

The maximum camber at the 25% span-wise position was positive during the latter half of the downstroke and the first half of the upstroke. In contrast, the maximum camber at the 50% and 75% span-wise positions was positive during the latter half of the downstroke and negative during the first half of upstroke. The absolute value of the maximum camber at the 50% span-wise position was larger than that at the 75% span-wise position.

![Figure 8](image)

Fig. 8 Time-variations of vertical forces $F$, $F_1$, $F_c$ and $F-F_1-F_c$ as described in the experimental section $-F_1-F_c$ by Eq. (4). This figure shows that the aerodynamic vertical force was large at the wing pronation ($t \approx 0$ s or $t \approx 27$ ms). This is experimental evidence that a large aerodynamic force is generated during pronation, which can not be explained by quasi-steady analysis. The aerodynamic vertical force decreased as the flapping angle decreased during the downstroke, except at $t = 0$. At the end of the downstroke, the aerodynamic vertical force was positive. This means the pressure of the upper surface of the wing was lower than that of the lower surface. At the beginning of the upstroke ($11$ ms < $t < 15.5$ ms), the aerodynamic vertical force decreased with increasing flapping angle. When $t > 15.5$ ms, the aerodynamic vertical force increased with increasing flapping angle. When $13$ ms < $t < 18$ ms, the aerodynamic vertical force was negative, indicating that the pressure of the upper surface of the wing was higher than that of the lower surface. The aerodynamic vertical force averaged during one flapping cycle was about $7$ mN, which is about 5 times stronger than the gravitational force acting on the moth (about 1.3 mN ($\approx m_{body}$)).

The phase difference between the time-variations of the feathering angle and that of the flapping angle was small (Fig. 5). This indicates the possibility that the feathering angle was affected by the inertial moment due to the flapping motion and that the axis of the feathering motion was closer to the leading edge than to the line connecting the center of gravity of the wing sections at span-wise positions. Note that when time-variation of the wing motion and that of the force or moment acting on the wing was either 0 or 180 deg., the force or moment might have caused the wing motion. However, the phase difference between the time-variation of the feathering angle and that of the aerodynamic vertical force was about 90 deg (Figs. 5 and 8). This phase difference indicates...
that the feathering angles was not affected by the moment due to aerodynamic force generated by the wings when the position of the pressure center of the wing section at the span-wise positions was fixed.

Feathering motion of the wings of the Diptera(18) and that of the hind wing of the scorpion fly(19) are caused by the inertial moment due to the flapping motion. These relations between the feathering motion and the inertial moment are common with that observed about the moth in the present experiment.

Figure 6 shows that the shape of the wing section at the 50% span-wise position resembled a "U". Figure 7 shows that the trend for the time-variation of maximum camber at 50% span-wise position was similar to that for the time-variation of the z coordinate (camber) at a specific chord-wise point at the 50% span-wise position. The phase difference between the time-variation of the maximum camber at the 50% span-wise position and that of the flapping angle was near 90 deg (Fig. 7). Therefore, the phase difference between the time-variation of the z coordinate (camber) at a specific chord-wise point at the 50% span-wise position and that of the flapping angle was almost 90 deg. This indicates that the z coordinate (camber) at a certain chord-wise point at the 50% span-wise position was not affected by the inertial force due to flapping motion. Similarly, at the 50% span-wise position, the phase difference between the time-variation of maximum camber, that is, time-variation of the z coordinate (camber) at a specific chord-wise point, and that of the feathering angle was almost 90 deg. The z coordinate (camber) at a certain chord-wise point at the 50% span-wise position was not affected by the inertial force due to feathering motion. And this camber change cannot be explained by the Ennos effect(14-15) (intimate link between wing torsion and camber generation), because the camber by the Ennos effect increases with the increase of torsion. In contrast, the phase difference between the time-variation of maximum camber at the 50% span-wise position and that of the aerodynamic vertical force was small (Figs. 7 and 8). The z coordinate (camber) at a certain chord-wise point at the 50% span-wise position was not affected by the inertial force due to flapping and feathering motions but by the aerodynamic force generated by the wing.

Wootton(20) suggested the cause of camber of the butterfly was caused by the aerodynamic force generated by the wing. This relation between the camber and the aerodynamic moment is common with that observed about the moth in the present experiment.

The advantage of the method used here, which was developed by Song et al.(19), is that deformation of a wing can be measured. However, the disadvantage is that the feathering angle cannot be measured during the entire flapping cycle. Furthermore, the vertical force measured by this method has higher accuracy when the insect is tethered at a point closer to the center of gravity of the insect's body, because the error due to the force Fzc is smaller as the tether point approaches the center of gravity.

4. Conclusions

Motion and deformation of the wings of a moth *Mythimna Separata* (Walker) tethered to a steel beam were measured by using an optical method that uses fringe pattern projection. Simultaneously, the vertical force due to aerodynamic force generated by the wings was estimated by measuring the bending deformation of the beam during flapping motion of the moth. The results obtained from these measurements are summarized as follows.

1. The feathering angles are mainly affected by the inertial moment generated by the flapping motion.
2. The wing camber is mainly affected by the aerodynamic force generated by the wing.
3. During the latter half of the upstroke and during wing pronation, the moth generated a positive aerodynamic vertical force that was significantly larger than its weight.

This research is supported by the National Natural Science Foundation of China 59875043 and 59925514, and by the Research and Development for Applying Advanced Computational Science and Technology, Japan Science and Technology.

References

(6) Buckholz, R.H., Measurements of Unsteady Peri-


