Handling parameters for rotational moment generation with four-wing flapping

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Abstract — The aim of this study was to clarify the relationships between pitch, roll, and yaw moments during flapping and various handling parameters ((i) wingbeat amplitude, (ii) stroke plane angle, and (iii) asymmetry of the flapping duration). We investigate the effects of the combination of (i) and (ii), or the combination of (i) and (iii) for generating rotational moments. The results demonstrated that flapping amplitudes and asymmetry contributed to generating pitch and roll moments, and flapping amplitude and tilt angle affected the generation of all moments.

Index Terms — rotational moments, wingbeat amplitude, stroke plane angle, asymmetric flapping duration.

I. INTRODUCTION

Generally, insects that fly by flapping their wings have impressive flying abilities, such as low-speed flight and hovering. Therefore, insects should be considered to have excellent attitude control mechanisms during flapping flight. Although nonstationary and nonlinear flow fields were generated during flapping flight in insects [1], insects controlled wing deformation and the flow around their wings adaptively by the structure of their wing veins and the shape of their wrinkle folds [2].

Adjusting the roll, pitch, and yaw moments acting on the insect body’s center of gravity (COG) is indispensable for attitude control during flapping flight. According to previous studies [3–5], attitude during flapping flight has been controlled through the development of a robot that mimics the flapping of two-winged insects. The generation of the pitch moment was demonstrated by changing the amplitude of flapping using a two-wing flapping model [6]. We also conducted research on the generation of roll and yaw moments in a two-wing model and clarified that the wingbeat amplitude affects the moment that acts on the COG [7–8]. On the contrary, studies on the generation of moments during attitude control in a four-wing model as compared to the two-wing model are few. Dragonflies flap their own four wings freely to achieve various flight abilities: hovering, high-speed forward flight, rapid turning, and sideways flight [9]. Isogai et al. [10] developed a four-wing dragonfly mimicking device and achieved attitude control while changing the flapping frequency of wings during flight. Isogai’s attitude control model [10] focused on controlling the roll and pitch moment; the model did not consider the generation of the yaw moment.

Controlling the generation of the number of moments should be necessary to deal with the aerodynamic forces in each wing. As with two-winged insects, the damselflies of *Calopteryx splendens* and *Lestes viridis* control their flight speed in the forward direction by changing two handling parameters independently: the temporal ratio of the forward stroke and the back stroke in one cycle (hereinafter referred to as asymmetry, α), and the stroke plane angle in one cycle (hereinafter referred to as the tilt angle) [11]. In these respects, although it is assumed that the forces and moments generated during flapping would be achieved independently of handling parameters such as flapping amplitudes, asymmetry, and tilt angle, or a combination thereof, the relationships and/or the phenomenon are still unclear. The aim of this study was to clarify the relationships between three moments (pitch, roll, and yaw) during flapping and the handling parameters by constructing special four-wing models and executing moment measurement experiments.

II. THE DEFINITION OF FOUR-WING FLAPPING AND THE GENERATION OF MOMENTS AS A FUNCTION OF HANDLING PARAMETERS

A. Definition of the coordinate system of a flapping model

Figure 1 shows the definition of the robot coordinate system (X-Y-Z). Let the X-axis be defined as the front direction of the robot, and the roll moment (Mx [Nm]) is around the X-axis, the pitch moment (My [Nm]) is around the Y-axis, and the yaw moment (Mz [Nm]) is around the Z-axis. During one cycle of flapping, the forward stroke phase was defined as when the wing moved in the positive direction of the X-axis, and the
back stroke phase was defined as when the wing moved in the negative X-axis direction. The lift force \( L_i \) was defined as a vertical force component to the stroke plane consisting of each \( i \)th \((i = 1, 2, 3, \text{ or } 4) \) wing, and the drag \( D_i \) was defined as a parallel force component to the stroke plane, as shown in Fig. 1.

![Fig. 1. Definition of the coordinate system of the four-wing flapping model](image)

**B. Averaged lift force and drag as a function of asymmetrical flapping between forward and back stroke phases**

When the flapping frequency is much larger than the eigen-frequency of an insect’s body, the influence of the wing on the body while hovering is the averaged lift force and drag during one cycle of flapping \([1]\). The averaged lift force \( L_i \) and drag \( D_i \) during one cycle of flapping are as follows:

\[
L_i = -\rho S C_L \frac{V_i^2}{2} \tag{1},
\]

\[
D_i = -\rho S C_D \left( \alpha_i V_i^2 + \frac{t_{b,i} V_{b,i}^2}{2} \right) \tag{2},
\]

\[
V_i = 2 n r \omega \Phi_i \tag{3},
\]

\[
V_{f,i} = n r \omega \Phi_i / t_{f,i} \tag{4},
\]

\[
V_{b,i} = n r \omega \Phi_i / t_{b,i} \tag{5},
\]

where \( \rho \) \([\text{kg/m}^3] \) is the fluid density around the wing, \( S \) \([\text{m}^2] \) is the representative surface area of the wing, \( C_L \) is the averaged coefficient of the lift force in one cycle, \( C_D \) is the averaged coefficient of the drag in one cycle, \( t_{f,i} \) is the temporal ratio during the forward stroke phase in one cycle, \( t_{b,i} \) is the temporal ratio during the back stroke phase in one cycle, \( V_i \) \([\text{m/s}] \) is the average speed of the \( i \)th wing in one cycle, \( V_{b,i} \) \([\text{m/s}] \) is the average speed of the forward stroke phase of the \( i \)th wing in one cycle, \( V_{b,i} \) \([\text{m/s}] \) is the average speed during the back stroke phase of the \( i \)th wing in one cycle, \( \Phi_i \), \( n \) Hz is the flapping frequency, and \( r \) \([\text{m}] \) is the length between the center of rotation of the flapping wing and the wing tip. It should be noted that \( C_L \) and \( C_D \) were constant since the average values of the lift force and the drag were considered in one cycle of flapping.

In the case of the dragonfly, the flapping frequency \((n)\) of each wing is equal in all four wings and does not contribute to changes in flight speed \([11–12] \). Also in this study, assuming that the flapping frequency \((n)\) is constant, the lift force \( L_i \) and the drag \( D_i \) are rewritten as follows:

\[
L_i = -\rho S C_L \frac{(2 n r \omega \Phi_i)^2}{2} \tag{6},
\]

\[
D_i = -\rho S C_D \frac{(n r \omega \Phi_i)^2}{2} \tag{7},
\]

\[
\alpha_i = 1/t_{f,i} - 1/t_{b,i} \tag{8},
\]

As shown in Eq. (6), the average lift force \( L_i \) is proportional to square of the flapping amplitude \( \Phi_i \); that is, \( L_i \propto \Phi_i^2 \). Also, the average drag \( D_i \) is proportional to the asymmetry \( \alpha_i \) and square of the flapping amplitude \( \Phi_i \), as shown in Eq. (7); that is, \( D_i \propto \alpha_i \Phi_i^2 \).

**C. Generation of moments for attitude control as a function of asymmetrical flapping**

In the case where the stroke plane of each wing is horizontal, in order to simplify the consideration of moment generation, the lift force and the drag generated by each wing were as follows:

\[
[F_{X,1}, F_{Y,1}, F_{Z,1}]^T = [D_{i}, 0, L_{i}]^T \tag{9},
\]

where \( F_{X,i}, F_{Y,i}, \) and \( F_{Z,i} \) are the forces for each axis. Hence, the generated moments were as follows:

\[
M_X = (F_{Z,1} - F_{Z,2} - F_{Z,3} + F_{Z,4}) r_Y \tag{10},
\]

\[
M_Y = (-F_{Z,1} + F_{Z,2} + F_{Z,3} + F_{Z,4}) r_Y \tag{11},
\]

\[
M_Z = (F_{X,1} - F_{X,2} - F_{X,3} + F_{X,4}) r_Z \tag{12},
\]

where \( r_x, r_y, \) and \( r_z \) are the moment arms for each axis, and the length of all moment arms are considered to be of equal lengths, since all four wings were the same. From the above definition and equations, the three moments are proportional to square of the wingbeat amplitude and/or the asymmetry of each wing as follows:

\[
M_X \propto \left( \Phi_1^2 + \Phi_2^2 + \Phi_3^2 - \Phi_4^2 \right) \tag{13},
\]

\[
M_Y \propto \left( -\Phi_1^2 - \Phi_2^2 + \Phi_3^2 + \Phi_4^2 \right) \tag{14},
\]

\[
M_Z \propto \left( \alpha_1 \Phi_1^2 - \alpha_2 \Phi_2^2 - \alpha_3 \Phi_3^2 + \alpha_4 \Phi_4^2 \right) \tag{15}.
\]

The notations of Eq. (13-15) are simplified as follows; \( M_{X,Y,Z} \propto \sum M_{XY,Z} \Phi_i^2 \), \( M_{X,Y,Z} \propto \sum M_{XY,Z} \alpha_i \Phi_i^2 \), \( M_{X,Y,Z} \propto \sum M_{XY,Z} \Phi_i^2 \), \( M_{X,Y,Z} \propto \sum M_{XY,Z} \alpha_i \Phi_i^2 \), \( M_{X,Y,Z} \propto \sum M_{XY,Z} \Phi_i^2 \).
above definition and equations, the three moments are proportional to square of the wingbeat amplitude and the tilt angle as follows:

\[
M_x \propto (\Phi_1^2 \sin \beta_1 - \Phi_2^2 \sin \beta_2) \\
M_y \propto (-\Phi_1^2 \cos \beta_1 + \Phi_2^2 \cos \beta_2 + \Phi_3^2 \cos \beta_3 - \Phi_4^2 \cos \beta_4) \\
M_z \propto (\Phi_3^2 \sin \beta_1 - \Phi_4^2 \sin \beta_2 + \Phi_3^2 \sin \beta_3 + \Phi_4^2 \sin \beta_4)
\]

(23), (24), (25),

\[
\beta_1 = \beta_{0,1}, \quad \beta_2 = \beta_{0,2}, \quad \beta_3 = \beta_{0,3}, \quad \beta_4 = \beta_{0,4}
\]

where \(\beta_{0,i}\) [rad] is the tilt angle as the vector of the lift force generated in each wing passed through the Y-axis, \(\beta_1\) [rad] is the difference between \(\beta_1\) and \(\beta_{0,1}\), as shown in Fig. 2. The notations of Eq. (23-25) are simplified as \(M_x \propto \sum \Phi^2 \cos \beta\), \(M_y \propto \sum \Phi^2 \sin \beta\), and \(M_z \propto \sum \Phi^2 \sin \beta\), respectively.

\[
\Phi_1 = \Phi_{i1}, \quad \Phi_2 = \Phi_{i2}, \quad \Phi_3 = \Phi_{i3}, \quad \Phi_4 = \Phi_{i4}
\]

where \(\Phi_{i,n}\) is the initial planes when the lift force vectors of each wing and \(Y\)-axis are normal to each other.

III. THE FOUR-WING FLAPPING MODEL INSTALLED MECHANISMS FOR MODULATING THE HANDLING PARAMETERS

We constructed two four-wing flapping models to demonstrate the relationships between the generation of moments and two handling parameters. One is the installed asymmetry modulation mechanism, and the other is the equipped tilt angle modulation mechanism. To negate the effects of wing size and/or deformation, both flapping models had the same wings installed; the shape was rectangular, the size of the wing was set to be 200 mm in the leading edge direction and 50 mm in the chord direction. Polypropylene sulfide resin film (Torrefan, TORAY Industries, Inc.) with a thickness of 15 \(\mu\)m was used for the wing. Carbon rods with a diameter of 1.0 mm were placed in a position corresponding to the major veins of the dragonfly wings, such as the costal vein and the MA (media anterior branch).

A. Four-wing flapping model with an asymmetry modulation mechanism

Fig. 3A shows the flapping mechanism for modulating the asymmetry to generate three moments (FMa). FMa could control the wingbeat amplitude (\(\Phi_i\)) of each wing independently, and all of the asymmetry parameters satisfy \(\alpha_i \neq 0\). The wingbeat amplitude of each wing is as follows:

\[
\Phi_i = \frac{2\sin^{-1}(r_c/l_i)}{r_c \cos^{-1}(r_c/l_i)}
\]

(27), where \(r_c\) [m] is the length of the crank arm link, as shown in Fig. 3A; \(l_i\) [m] is the length between the center of the rotation of flapping and the center of the rotation of the crank arm link. The wingbeat amplitude could be modulated by arbitrary changes in \(l_i\). Let asymmetry \(\alpha_i\) using FMa according to the geometrical constraints be derived as follows:

\[
\alpha_i = \frac{\omega_c}{4r_c \cos^{-1}(r_c/l_i)} \left[ \pi - 2\cos^{-1}(r_c/l_i) \right]
\]

(28), where \(\omega_c\) [rad/s] is the rotational velocity. From Eq. (28), it can be seen that the \(\alpha_i\) varies according to the \(l_i\), as well as the \(\Phi_i\). Therefore, it is considered that the generation of the average drag as a function of the \(\alpha_i\) should be enhanced by the increase of the \(\Phi_i\). The direction of the average drag generated using FMa could be controlled by changing the rotational direction of the crank arm link; (1) when the crank arm for the first and fourth wings moves in the clockwise direction \((\alpha_i > 0)\), as shown in Fig. 3, then \(\alpha_i > 0\) and \(D_r > 0\), (2) when the crank arm for the second and third wings are moved simultaneously in the counterclockwise direction \((\alpha_i < 0)\), then \(\alpha_i < 0\) and \(D_r < 0\).

![Fig. 2. Definition of the stroke plane angle in the forewings and hind wings. Thick black lines indicate the stroke planes. Thin black lines indicate the initial planes when the lift force vectors of each wing and Y-axis are normal to each other.](image)

![Fig. 3. Flapping mechanism considering asymmetry: FMa. (A) FMa had the slider-crank mechanism installed to control the flapping amplitude. (B) Photo of experimental model FMa.](image)
and the wingbeat amplitude ($\Phi_i$), using four servo motors (GWS S11 HP/2BB Double Ball Bearing Servo, Grand Wing Servo-Tech Co., Ltd.). The wingbeat amplitude ($\Phi_i$) was controllable from 0.480 to 0.895 [rad], and the phase lags between all wings during flapping were equal. The size of the FMα, except the wing, was 150 mm (width), -150 mm (depth), and -90 mm (height).

B. Four-wing flapping model with a tilt angle modulation mechanism

Fig. 4 shows the flapping mechanism needed to achieve tilt angle modulation for generating three moments (FMβ). FMβ could control the flapping amplitude ($\Phi_i$) of each wing independently, and the tilt angles of the forewings ($\beta_f$) and/or hind wings ($\beta_h$). To reduce the effect of asymmetry ($\alpha_i=0$) during flapping, the flapping motion was achieved by converting the reciprocating motion by the Scotch yoke mechanism into a swing motion by the swinging slider crank mechanism, as shown in Fig. 4A. The flapping amplitudes ($\Phi_i$) achieved by FMβ are similar to those of FMα, as shown in Eq. (27) and Fig. 4A. Furthermore, as shown in Fig. 4B, the tilt angle ($\beta$) could be handled by a four-link mechanism. Fig. 4C shows FMβ, which could control the flapping frequency ($n$), using a brushless motor (AX-2213N, Amico), and the wingbeat amplitude ($\Phi_i$) and the tilt angle of the forewing ($\beta_f$) and the hind wing ($\beta_h$) using six servo motors (HXT500, Hextronik Limited HK). The wingbeat amplitude ($\Phi_i$) was controllable from 0.611 to 1.222 [rad], and the phase lags between all wings were equal. The tilt angles ($\beta_f$ and $\beta_h$) could be adjusted from 0.698 to 1.390 [rad]. The size of FMβ except the wing was 150 mm (width), -200 mm (depth), and -200 mm (height).

C. Calculation of the Reynolds numbers and reduced frequencies of both flapping models

In a flapping model-based study, it is necessary to reproduce a fluid dynamic condition similar to an insect’s situation, such as a Reynolds number (Re) [13–14] and/or the reduced frequency [12, 15]. In the case of flapping insects, the Re would be denoted as follows:

$$Re = \frac{rv}{\nu}$$  \hspace{1cm} (29),

where $r_m$ is the average wing chord, $V$ [m/s] is the average speed of the wing tip, and $v$ [m$^2$/s] is the kinematic viscosity around the wing. Previously, the range of the Re had been reported as being from $10^3$ to $10^5$ in flapping insects [16]. In this study, when the flapping frequency was 3.0 Hz and the kinematic viscosity was $1.512 \times 10^{-5}$ m$^2$/s, the Re of FMα was in the range of 2600 to 4800, and the Re of FMβ was 3200 to 6600. Therefore, our flapping models, FMα and FMβ, satisfy the Re of flapping insects.

There are other parameters to demonstrate the nonstationary fluid dynamic characteristics, such as the Strouhal number (St, [17]), and the reduced frequency ($k$, [12, 15]). In this study, reduced frequency $k$ was adopted to demonstrate the nonstationary fluid dynamic characteristics during hovering, since the St is a parameter for forward flight and could not be used to evaluate the phenomenon of hovering.

The reduced frequency $k$ is as follows:

$$k = \frac{\pi nr}{V}$$  \hspace{1cm} (30).

To our knowledge, there has been no research that derives the reduced frequency $k$ and/or reduced frequency of four-wing flapping, such as that of the dragonfly.
that of forward flight speed, and the value of \( k \) was in the range of 0.25 to 0.44. When the flapping frequency was set at 3 Hz in this study, the \( k \) of FM\( \alpha \) was in the range of 0.33 to 0.61, and the \( k \) of FM\( \beta \) was in the range of 0.23 to 0.48. Therefore, FM\( \alpha \) and FM\( \beta \) are equivalent to the reduced frequency of the dragonfly, and it can be said that the evaluation of four-wing flapping using our model is reasonable.

IV. EXPERIMENTS TO MEASURE RESULTANT MOMENTS AS A FUNCTION OF HANDLING PARAMETERS

A. Aim of the experiments

The purpose of these experiments was to clarify the relationships between the handling parameters (asymmetry, \( \alpha_i \) and tilt angle, \( \beta_i \)) and the resultant moments \( (M_x, M_y, M_z) \) for attitude control during four-wing flapping using FM\( \alpha \) and FM\( \beta \).

B. Methods

The flapping frequency of FM\( \alpha \) and FM\( \beta \) were set at 3 Hz. A commercial real-time 3D motion analysis system with six cameras (VENUS3D, Nobby Tech. Ltd.) was used to measure the flapping amplitude of FM\( \alpha \) and FM\( \beta \). A 6-axis optical force transducer (OPFT-50N-B with OPFT-SCPI, Minebea Co., Ltd.) was installed to detect the generated three moments during flapping with a 1-kHz sampling frequency. The flapping amplitude and the moment profiles were recorded in synchronization. Both of FM\( \alpha \) and FM\( \beta \) cannot reject the possibility of the offset of COG location from its origin when placed on the force transducer. Therefore, from the moment profiles, representative values for each moment during flapping in one cycle were calculated as the deviation between the wings stayed at the center of the amplitude under a static condition and the average value of the moment data. A fourth-order Butterworth filter was applied to the flapping angle and the moment data with a cutoff frequency of 10 Hz for offline analysis.

The combinations of the handling parameters are shown in Tables 1, 2, and 3. Different experimental conditions for \( M_x \) and \( M_y \) (as shown in Table 2) and for \( M_z \) (as shown in Table 3) were established to simplify the experimental conditions in FM\( \beta \). In addition, \( \beta_{0,i} \), as shown in Eq. (26), were set at \( \beta_{0,i} = 5 \) deg and \( \beta_{0,h} = 15 \) deg based on the relative position of the force transducer. In either condition, five consecutive flapping cycles were measured and analyzed.

C. Results

Fig. 5A shows typical averaged results of the \( M_x \) during flapping in one cycle at conditions of A7 and A10 using FM\( \alpha \). As shown in Eqs. (13) to (15), a proportional relationship is assumed to be the square of \( \Phi_i \) and three moments during flapping by FM\( \alpha \). In fact, the generated \( M_x \) seems to be in more a symmetrical pattern under the experimental condition of A7 as compared to that of A10 (Fig. 5A).

| Experimental conditions | Parameters | \( \Phi_1 \) | \( \Phi_2 \) | \( \Phi_3 \) | \( \Phi_4 \) | \( \beta_f \) | \( \beta_h \) |
|------------------------|------------|---------------|---------------|---------------|---------------|---------------|---------------|
| B1                     | min        | min           | min           | min           | min           | min           | min           |
| B2                     | min        | max           | max           | min           | min           | min           | min           |
| B3                     | max        | min           | min           | max           | min           | min           | min           |
| B4                     | min        | min           | min           | min           | mid           | mid           | mid           |
| B5                     | max        | max           | mid           | max           | mid           | mid           | mid           |
| B6                     | max        | min           | max           | mid           | mid           | max           | max           |
| B7                     | min        | min           | min           | max           | min           | max           | max           |
| B8                     | max        | min           | min           | max           | max           | max           | max           |
| B9                     | max        | min           | min           | max           | max           | max           | max           |

Regard to \( \Phi_i \), min = 0.611[rad], max = 1.222[rad].
Regard to \( \beta_i \), min = 0.698[rad], mid = 1.047[rad], max = 1.396[rad]

To clarify these phenomena, Fig. 5B, C, and D demonstrates the results of the linear regression lines with regression coefficients between the square of \( \Phi_i \) and the three moments. Although the relationships between \( \sum M_x \Phi_i^2 \) and \( M_x \) or \( \sum M_y \Phi_i^2 \) and \( M_y \) show high correlations with more than 0.8 of regression coefficients, no correlation between \( \sum M_z \alpha \Phi_i^2 \) and \( M_z \) was confirmed.

| Experimental conditions | Parameters | \( \Phi_1 \) | \( \Phi_2 \) | \( \Phi_3 \) | \( \Phi_4 \) | \( \beta_f \) | \( \beta_h \) |
|------------------------|------------|---------------|---------------|---------------|---------------|---------------|---------------|
| A1                     | min        | min           | min           | min           | min           | min           | min           |
| A2                     | min        | min           | min           | max           | min           | min           | min           |
| A3                     | min        | min           | max           | min           | min           | min           | min           |
| A4                     | min        | min           | max           | max           | min           | max           | max           |
| A5                     | min        | max           | min           | min           | min           | min           | min           |
| A6                     | min        | max           | min           | max           | min           | min           | min           |
| A7                     | min        | max           | max           | min           | max           | max           | max           |
| A8                     | min        | max           | max           | max           | min           | max           | max           |
| A9                     | max        | min           | min           | min           | min           | max           | max           |
| A10                    | max        | min           | min           | min           | max           | max           | max           |
| A11                    | max        | min           | max           | min           | min           | max           | max           |
| A12                    | max        | min           | max           | max           | min           | max           | max           |
| A13                    | max        | min           | max           | max           | min           | max           | max           |
| A14                    | max        | max           | min           | max           | min           | max           | max           |
| A15                    | max        | max           | max           | max           | min           | max           | max           |
| A16                    | max        | max           | max           | max           | max           | max           | max           |

Regard to \( \Phi_i \), min = 0.480[rad], mid = 0.687[rad], max = 0.895[rad]
Table 3 Experimental conditions of $M_y$ for FMβ

| Parameters | $\Phi_1$ | $\Phi_2$ | $\Phi_3$ | $\Phi_4$ | $\beta_f$ | $\beta_h$ |
|------------|----------|----------|----------|----------|----------|----------|
| C1         | min      | min      | min      | min      | min      | min      |
| C2         | min      | min      | max      | min      | min      | min      |
| C3         | max      | max      | min      | min      | min      | max      |
| C4         | min      | min      | min      | min      | min      | max      |
| C5         | min      | min      | max      | min      | min      | max      |
| C6         | max      | max      | min      | min      | min      | max      |
| C7         | min      | min      | max      | min      | min      | max      |
| C8         | min      | min      | max      | min      | max      | max      |
| C9         | max      | min      | max      | min      | max      | max      |

Regard to $\Phi_i$, min = 0.611 [rad], max = 1.222 [rad].
Regard to $\beta_j$, min = 0.698 [rad], max = 1.396 [rad].

Fig. 6A shows typical averaged results of the $M_z$ during flapping in one cycle at the conditions of B8 and B9 using FMβ. As shown in Eqs. (23) to (25), the proportional relationships are also assumed to be \( \sum \Phi^2 \cos \beta \), \( \sum \Phi^2 \sin \beta \), and \( \sum \Phi^2 \sin \beta \) for the three moments during flapping by FMβ. In fact, the generated $M_z$ seems to have a symmetrical pattern under the experimental condition of B8, as compared to that of B9 (Fig. 6A). To clarify these phenomena, Fig. 6B, C, and D demonstrates the results of the linear regression lines with regression coefficients between \( \sum \Phi^2 \cos \beta \), \( \sum \Phi^2 \sin \beta \), and \( \sum \Phi^2 \sin \beta \) for the three moments, respectively. The relationships between \( \sum \Phi^2 \cos \beta \) and $M_x$, \( \sum \Phi^2 \sin \beta \) and $M_y$, or \( \sum \Phi^2 \sin \beta \) and $M_z$ show high correlations with more than 0.8 of regression coefficients.

D. Discussion

The main finding of this study was clarification of the different effects of the handling parameters on generating the pitch, roll, and yaw moments of four-wing flapping mechanisms. In the case of asymmetry, the result showed that the regression coefficient for the yaw moment by FMα had no significant effect, since the asymmetry had little effect on the generation of and/or control of the moments during two-wing flapping [18]. In the case of the tilt angle, the regression coefficient between \( \sum \Phi^2 \sin \beta \) and $M_y$ by FMβ was lower as compared to the results of FMα. This would reflect the existence of the unstable oscillatory mode in the pitch direction, since inclined stroke-plane hovering flight is not stable [19]. These results suggest that the handling parameters of asymmetry and the tilt angle have different effects to generate all three moments.

As shown in Fig. 5A ($M_x$ on FMα) and in Fig. 6A ($M_z$ on FMβ), the peaks and valleys were almost in phase with each other up to around 0 to 50% of stroke cycle. However, especially in 50-75% of stroke cycle, this aspect disappeared or declined. Since this phase is just after switching between forward stroke and backward stroke, we cannot reject the possibility that the wing formed precisely and the wing deformation while flapping.

Fig. 5. (A) Typical results of $M_x$ at conditions A7 (gray line) and A10 (black line) on FMα. Dashed lines indicate standard divisions of each moment wave. Gray and black horizontal lines indicate average values corresponding to each condition. (B) Result of regression analysis of the roll moment. (C) Result of regression analysis of the pitch moment. (D) Result of regression analysis of the yaw moment.
Fig. 6. (A) Typical results of $M_z$ at conditions B8 (gray line) and B9 (black line) on FMβ. Dashed lines indicate standard divisions of each moment wave. Gray and black horizontal lines indicate average values corresponding to each condition. (B) Result of regression analysis of the roll moment. (C) Result of regression analysis of the pitch moment. (D) Result of regression analysis of the yaw moment.

Previous study had demonstrated that the aerodynamic efficiency could be improved by removing the swirl while four-wing flapping. This phenomenon was achieved by a fore-hind wing phase shift and the differences in the stroke plane of fore-hind wing [20]. In this study, using FMβ, the position of the stroke plane of fore-hind wings is changed as compared to FMα. With respect to our results and the previous study [20], the tilt angle and the arrangement of the stroke plane of fore-hind wing would be important to generate the yaw moment while four-wing flapping.

Further studies are needed to measure the flow field around the wing during four-wing flapping while modifying the handling parameters, since the leading edge vortex is an important feature of the flows created by insect wings and, thus, the forces they create [15]. In addition, recent studies have demonstrated that the wing rotation angle and/or the deflection angle at the wing root play an important role in generating the control moment in roll rotation and/or maximum translational force generation [21–23].

V. CONCLUSION

We investigated the effects of combinations of the handling parameters for generating the pitch, roll, and yaw moments during four-wing flapping. The combination of the wingbeat amplitude and the asymmetry contributed to generating the pitch and roll moments, but not the yaw moment. On the other hand, the combination of the wingbeat amplitude and the tilt angle for generation plays an important role in generating all three moments. These results suggest that the handling parameters of asymmetry and tilt angle have different effects to generate all three moments. During four-wing flapping, controlling the combination of the wingbeat amplitude and the stroke plane angle to generate the pitch, roll, and yaw moments has advantages among the handling parameters of the combination of the wingbeat and the asymmetry of the flapping duration.

VI. APPENDIX

Here, the asymmetry while flapping using slider crank mechanism shown in Fig. 3(A) will be described in detail. Fig. A1 show the simplified slider-crank mechanism used in this study. The flapping amplitude is ($\Phi$), and set points as shown in figure, and set angle (BOC) = angle (BOA) = $\theta$.

![Fig. A1. Simplified slider-crank mechanism as shown in Fig. 3(A).](image-url)
The asymmetry \( \alpha(t) \) of the forward stroke and the backward stroke can be obtained geometrically as the ratio of the arc length (short side of \( AĈ_{\text{short}} \) v.s. long side of \( AĈ_{\text{long}} \)). The central angle for \( AĈ_{\text{short}} \) is \( 2\theta \), and \( (2\pi - 2\theta) \) for \( AĈ_{\text{long}} \). Although the asymmetry would be disappeared when \( OB \) goes to \( +/-\), there is always asymmetry as \( OB \) has a finite length \( (OB = l) \). When the crank arm \( (r_c) \) rotates at the angular velocity \( \omega_c \), the times required for the forward \( (t_f) \) and backward stroke \( (t_b) \) are as follows:

\[
\theta = \cos^{-1}(r_c/l_i) \quad (A1),
\]
\[
AĈ_{\text{long}} = 2\pi r_c \frac{2\pi - 2\theta}{(2\pi)} \quad (A2),
\]
\[
AĈ_{\text{short}} = 2\pi r_c \frac{\theta}{(2\pi)} \quad (A3),
\]
\[
t_f,i = \frac{AĈ_{\text{long}}}{\omega_c} \quad (A4),
\]
\[
t_b,i = \frac{AĈ_{\text{short}}}{\omega_c} \quad (A5).
\]

Thus, the asymmetry is calculated as follow:

\[
\alpha_i = 1 - t_f,i - 1/ t_b,i \quad (8),
\]
\[
= \frac{\omega_c - \pi + 2\theta}{4\pi r_c^2 \frac{\pi - \omega_c}{\pi - \omega_c}} \quad (A6),
\]
\[
= \frac{\omega_c - \pi + 2\cos^{-1}(r_c/l_i)}{4\pi r_c \cos^{-1}(r_c/l_i) \frac{\pi - \omega_c}{\omega_c}} \quad (30).
\]

VII. ACKNOWLEDGEMENTS

Part of this project was supported by KAKENHI, Grant-in-Aid for Exploratory Research, Grant Number 24650089.

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