Numerical investigation of the aerodynamic characteristics of a hovering Coleopteran insect

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1. Introduction

Understanding how flapping mechanisms generate outstanding aerodynamic performance has been a major focus of insect flight research in recent years (Ellington et al., 1996; Wang, 2000b). The research includes accurate quantification of complex kinematics of flapping insect wings, measurement of forces produced by flapping wings, and visualization of flows developed around wings. Visualization tools such as the smoke wire technique (Thomas et al., 2004) and the digital particle image velocimetry technique (Bomphrey et al., 2005) have enabled researchers to formulate the basic flapping mechanism of insects. These techniques have revealed that the flow characteristics of flapping flight differ from those of non-flapping flight.

The application of smoke visualization techniques inside a wind tunnel enables the vortices generated by an insect’s wings to be observed (Grodntsky and Morozov, 1992; Willmott et al., 1997). However, it is extremely difficult to obtain repeatable airflow data from live insects because of their small size and handling difficulty. Researchers have used two strategies to overcome these limitations. The first approach is to construct a scale-up robotic insect for direct measurement of aerodynamic forces and visualization of the flow characteristics. Such robotic insect is much easier to manipulate and duplicate its motion than that of a living insect (Berg and Ellington, 1997; Dickinson et al., 1993, 1999). The second approach utilizes computational fluid dynamics to simulate flapping wings (Sun and Lan, 2004; Wang, 2000a, 2004; Zuo et al., 2007; Ishihara et al., 2009).

During flight, an insect wing produces a leading-edge vortex. This vortex has a helical shape, and it is stably attached on a wing during the wing’s downstroke (Berg and Ellington, 1997; Birch and Dickinson, 2001; Ellington et al., 1996; Lu and Shen, 2008; Lentink and Dickinson, 2009). Three mechanisms, namely the delayed stall, rotational circulation, and wake capture mechanisms, were proposed to explain the flapping wing flight of insects (Birch et al., 2004; Dickinson et al., 1999; Fry et al., 2003). They attempted to prove their theory by constructing and using dynamically scaled-up robotic wings to acquire quantitative velocity data via a digital particle image velocimetry technique. Various kinds of vortex were found through recent 3D vortex structure analysis (Bomphrey et al., 2005; Sun and Lan, 2004). When a wing movement is accompanied with flapping, lagging and rotating, vortices such as leading-edge vortex, trailing-edge vortex, wing-base vortex, upper surface vortex, and lower surface vortex and axial flow are observed (Zuo et al., 2007). During the early downstroke and upstroke, a horseshoe-shaped primary vortex is observed to wrap around each wing, doughnut-shaped vortex rings break up into two circular vortex rings as they propagate downstream in the wake in a hovering hawkmoth study (Aono et al., 2009).

Researchers have been using the computational fluid dynamics to simulate the insect flapping wings as a means of investigating
the details of the insect flight mechanism (Liu and Kawachi, 1998; Sun and Lan, 2004; Wang and Russell, 2007; Kim et al., 2009). Wang (2000a) developed a computational fluid dynamic code to simulate a 2-D flapping wing. Her numerical results revealed that a downward dipole jet is formed from the leading-edge and trailing-edge vortices. A comparison of a 2-D numerical simulation and 3-D experiments of scaled-up robotic fly wings was recently published (Wang et al., 2004). From this comparison, the main difference between a 3-D revolving wing and a 2-D translating wing is the absence of vortex shedding in a 3-D wide domain by a revolving wing, though this absence of vortex shedding has a negligible effect in the case of a small translational distance. Other main phenomena, namely leading-edge vortex shedding and a delayed stall, were also observed in the 3-D simulations just as they were in the 2-D simulations; these phenomena explain the high lift mechanism (Ramamurti and Sandberg, 2002; Zuo et al., 2007). 2D simulation was performed to compute the aerodynamic force and power of dragonfly as a function of the phase. The out-of-phase motion used in steady hovering spends nearly minimal power to generate the required force to balance the weight, and the in-phase motion seen in takeoffs provides an additional force to accelerate the body (Wang and Russell, 2007). The vortex in the corrugation valleys near the leading-edge forms smooth streamline around the wing like an airfoil, and relatively reduces the drag coefficient in steady simulation (Kim et al., 2009).

The study of insect flight is motivated by the need to understand the flapping mechanism and by the practical purpose of producing an unmanned air vehicle based on the flapping wing mechanism instead of a conventional fixed wing. Flapping-type unmanned air vehicles can operate in extreme environmental conditions, as in the case of a Mars exploration mission (Ellington, 1999; Ho et al., 2002). Insect species such as the dragonfly, fruit fly, butterfly, and hawkmoth have been used as typical models for insect flapping flight (Buckholz, 1981; Srygley and Thomas, 2002). Several methods were proposed to measure 3D body and wing kinematics of free-flying insects (Ristroph et al., 2009, Zhang et al., 2008). However, few investigators have studied the flight mechanism of the Coleopteran insect. The wing system of the Coleopteran insect is uniquely composed of highly flexible hind wings that are folded and covered by a stiff elytron (fore wing). This mechanism differs from that of a dragonfly, cicada, and butterfly, which all have a front and rear wing configuration. Recently, microstructures and mechanical properties of the elytron have been investigated (Dai and Yang, 2009).

In this paper, we present the aerodynamic performance of the hind wing and elytron of a Coleopteran insect in hovering flight. We created a flapping kinematics model on the basis of experimental observation and then used the model in a 2-D numerical simulation. We systematically studied the kinematics of the Coleopteran insect flapping wing to gain a better understanding of the interaction between the elytron and the hind wing in hovering flight condition.

2. Materials and methods

2.1. Experimental method

A digital high-speed camera (Photron Inc., APX) was used to observe the wing kinematics of a Coleopteran insect in hovering flight. The Coleopteran insect *Epilachna quadricollis* was released into an enclosed cubic chamber made of transparent acrylic. The dimensions of the chamber were 50 cm × 50 cm × 50 cm. The insect had a body length of around 1.0 cm, a wing span of 1.2 cm, and a maximum wing chord of 0.6 cm. The high-speed camera was orthogonally aligned and located outside the acrylic chamber, and a halogen lamp was used as a light source. Images of the Coleopteran insect wing motion were taken with the high-speed camera at 2000 fps in a shutter time of 1 μs and a screen resolution of 1024 × 1024 pixels. Fig. 1 shows the setup of the experimental apparatus for this observation.

2.2. Numerical method

To investigate the aerodynamic characteristics, we performed a 2-D numerical simulation by using the commercial software program ADINA (2008). Here we considered hovering flight of Coleopteran insect. After obtaining the wing kinematics from the experiment, we implemented the hovering flight condition into the numerical simulation. Hence the advance ratio is definitely zero, where the advance ratio is defined as the ratio of forward velocity and wing tip velocity (Dickson and Dickinson, 2004). The wing geometry was modeled as a simple 2-D elliptic model. The hind wing is composed of a thin membrane and veins, which form the bumpy (cambered and corrugated pattern) structure of the cross section. For simplification, we therefore assume that the wing shape is elliptic.

The governing equations of the flow are described by the 2-D unsteady incompressible Navier–Stokes equation as follows:

\[ \nabla V = 0, \]  
\[ \rho \frac{\partial V}{\partial t} + \nabla (\rho V V - \tau) = f_b, \]

where \( t \) is the time, \( \rho \) is the density of air, \( V \) is the velocity vector, \( f_b \) is the body force vector of the fluid medium, and \( \tau \) is the stress tensor. The \( \tau \) equation is \( \tau = -p I + 2\mu e \), \( p \) is the pressure; \( I \) is the identity matrix; \( \mu \) is the dynamic coefficient of fluid viscosity; and \( e \) is the velocity strain tensor, which is expressed as \( e = 1/2(\nabla V + \nabla V^T) \).

The Reynolds number is defined as

\[ Re = \rho \frac{V_{\text{max}}}{\mu} c, \]

where \( c \) is the chord length and \( V_{\text{max}} \) is the maximum translation velocity of a hind wing during flapping. The value of \( V_{\text{max}} \) is obtained in the body-coordinate frame. While the flaps up and down, the flapping speed reaches a maximum value at the middle of the downstroke or at the middle of the upstroke. Another non-dimensional parameter, the Strouhal number, is usually considered for insect flight or for plunge and oscillation motions where the flow should have a forward velocity. Because this study
examines 2-D hovering flight, the Strouhal number is not considered a significant parameter.

The aerodynamic forces acting on the wing can be computed by integrating the stress terms on the upper and lower surfaces of the wing model. Then, the vertical force $F_V$ and horizontal force $F_H$ can be easily calculated by transforming the total force into the $x$ and $y$ directions. The non-dimensional coefficients, $C_V$ and $C_H$, used to express the vertical and horizontal forces, are defined as:

$$C_V = \frac{2F_V}{\rho U_{\text{max}}^2}, \quad C_H = \frac{2F_H}{\rho U_{\text{max}}^2}.$$  

(4)

The vorticity field is an important parameter that explains the force generation in a flapping wing. From a 2-D perspective, it can be calculated as

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y},$$

(5)

where $v$ and $u$ are the velocity in the $y$ and $x$ directions in an $x$-$y$ coordinate.

To investigate the effect of wing flexibility, we modeled the chordwise flexible wing with a fluid–structure interaction (FSI) solver, as shown in Fig. 2. We used only one structure mesh system for our simulation with the elliptic shape wing model and the computational domain is rectangular shape (far-field boundary). Therefore it is difficult to generate mesh system with perfect elliptic shape around the wing. FSI problems have recently been described and solved in the ADINA program (Bathe and Zhang, 2004; Bathe and Ledezma, 2007). The structural wing model is composed of 2-D solid elements with a uniform structural property. The model has two parts: part 1, as indicated in Fig. 2, is a small circle inside the elliptic wing body, which has a rigid link. Therefore, the part 1 definitely has motions as a rigid body under described motion of a control point. Part 2 is modeled as an elastic wing with a typical Young’s modulus ($E$) of 1 GPa and a Poisson’s ratio ($v$) of 0.3. The transfer motion from part 1 to part 2 is implemented by the joint element on the boundary line between them. The Young’s modulus and the Poisson’s ratio were estimated for the present simulation based on the reference of previous studies: the modulus of the membrane of the cicada wings was approximately 3.7 GPa (Song et al., 2004). More recently, it was found that Young’s moduli of a beetle hind wing membrane are different in the chordwise and spanwise directions (Jin et al., 2009).

The governing equations for solids with large displacements with relatively small strains are as follows:

$$M^{(t)} + \Delta M^{(t)} \ddot{U} + C^{(t)} \dot{\Delta U} + K^{(t)} \Delta U = R^{(t)} - F^{(t)},$$

(6)

where $M$ is the mass matrix; $C$ is the damping matrix; $K$ is the stiffness matrix taken as constants; $R$ is the external load vector at time $t + \Delta t$; $F$ is a force vector equal to the element stresses at time $t$; and $\dot{U}$, $\ddot{U}$, and $U$ represent the acceleration, velocity, and displacement, respectively. Eq. (6) was solved by using the Newton method for an iteration scheme with a convergence tolerance of 0.001.

The FSI solver uses interactive coupling, where the governing equations for the fluid and structure domain are solved individually and in succession (Bathe and Zhang, 2009). The conditions of the displacement compatibility and traction equilibrium along the structure–fluid interfaces are satisfied as follows:

$$d_f = d_s,$$

(7)

$$f_f = f_s,$$

(8)

where $d$ and $f$ are displacement and traction values, and the subscripts $f$ and $s$ stand for the fluid and solid, respectively.

2.3. Validation by harmonic wing kinematics

The accuracy and performance of the ADINA program for the 2-D simulation were validated by comparing the aerodynamics of a hovering dragonfly with a reference solution (Kim and Choi, 2007). Kim and Choi (2007) used a kinematics model prepared by the harmonic functions derived by Wang (2000b). Using inclined stroke planes in hovering flight, a dragonfly can support its weight with vertical force. As illustrated in Fig. 3, the results were gathered after five cycles, and the present results show good agreement with the reference solution. The vertical force is mostly generated during the downstroke period, whereas most of the thrust force is generated during the upstroke period. In Fig. 3, a time period from 5.0 to 5.5 ($t/T$) is for a downstroke and the other period from 5.5 to 6.0 is for an upstroke.

3. Results and discussion

3.1. Wing flapping kinematics

The kinematics of the closing and opening of the elytron are acquired from captured images (Frantsevich et al., 2005). The kinematic motions of the hind wing were measured at the middle of the wing along the spanwise direction. The motion of hovering flight was recorded during three cycles from a side view, and the
kinematic data were obtained by averaging three sets of data. The estimated errors of the $x$ and $y$ translation and rotational angle are less than 9%, 33%, and 4%, respectively. With a hind wing chord length of about 6 mm at the middle of span, the Epilachna quadricollis flaps its hind wings in a stroke plane inclined about $-10^\circ$ from the horizontal direction, as shown in Fig. 4. There are 16 frame images for one stroke cycle of hovering motion, which means the flapping period, $T$, is equal to 8 ms. Therefore, the flapping frequency, $f$, is equal to 125 Hz. The amplitude of the stroke plane is 2 cm; hence, the average wing translational velocity calculated from the amplitude and period time is around 5 m/s at the middle span of the wing. The downstroke to upstroke ratio of the flapping motion averages about 1, which is a little different from the corresponding ratio of other insects.

From the experimental observations, we modeled the following coordinates ($x_h$, $y_h$) and angle of the chord line, $\alpha_h$, from the horizontal direction of the hind wing by inserting some parameters into previous ideal harmonic kinematic models:

$$x_h = 0.5 \times 2 \cos(2\pi 125t) \cos(-\pi/18),$$

$$y_h = 0.5 \times 2 \cos(\delta - 2\pi 125t) \sin(-\pi/18),$$

$$\alpha_h = \pi/2 - (\pi/4) \times \sin(2\pi 125t) + \alpha_t,$$

where $\delta$ and $\alpha_t$ are the parameters used at each time step so that the idealized harmonic functions can be fitted to the acquired experimental data shown in Fig. 5.

With regard to the elytron, the chord length is 4 mm and the stroke angle of the flapping is $37^\circ$. However, the stroke plane amplitude of the elytron is only 0.75 times the chord length. The rotational angle is demonstrated as a linear function. The rotational angle is increased gradually from 74° to 80° during the downstroke and then reduced to 74° during the upstroke. It is noticeable that the stroke amplitude and the rotational angle are smaller than the hind wing. The wing kinematics of the elytron was also modeled (Frantsevich et al., 2005) as follows:

$$x_e = 0.5 \times 0.3 \cos(2\pi 125t) \cos(37\pi/180),$$

$$y_e = 0.5 \times 0.3 \sin(2\pi 125t) \sin(37\pi/180),$$

$$\alpha_e = \pi/90 \times (\pi/30) \times 2t/T,$$

where subscript $e$ means the quantities of the elytron. The translational motions are the same as the ideal harmonic motions, though the angle of attack is modeled as a linear function. Fig. 4 shows the kinematic flapping motions of both the elytron (camber shape) and the hind wing (elliptic shape). In the following sections, we present the numerical simulation results for the aerodynamic characteristics with the flapping kinematic models.

The flapping frequencies are approximately 250, 125 and 40 Hz for honeybee, Coleoptera, and dragonfly, respectively (Zhang et al., 2008). These values indicate that as body size of insect is smaller the flapping frequency is higher. The dragonfly has two pairs of wings which are in same size and shape and active for generating the aerodynamic force, while the hind wing of Coleoptera, which is larger than the elytron, is considered as the main source for aerodynamic force. In the meantime, the hind wing of Coleoptera can fold and unfold more skillfully compared to other insects including dragonfly. The protecting role of the elytron provides more flexibility to the hind wing.

### 3.2. Hovering flight of a coleopteran insect

The focus of the 2-D simulation of hovering flight is on the hind wing rather than the elytron. We assumed the hind wing to be a rigid elliptic wing. The numerical simulation results of the dragonfly suggest that the modeling of the wing as an elliptic wing or a flat plate produces no significant difference in the force distribution (Kim and Choi, 2007). The sharpness of the leading edge of the wing may have a critical effect on separation. The
Fig. 7. Vortex field contour during one cycle of hind wing flapping (blue: clockwise; red: counterclockwise). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 8. Pressure field contour during one cycle of hind wing flapping.
protruding corners of corrugated wing can be considered as a "tabulator" to generate unsteady vortices within the inter-pleat regions, which delay flow separation (Kim et al., 2009; Tamai et al., 2007). The fluid has a density of $1.225 \times 10^{-3}$ g/cm$^3$ and a dynamic viscosity of $1.875 \times 10^{-4}$ g/cm s, and these values correspond to a standard air condition. In addition, the fluid has a Reynolds number of 3141.

The size of the computational domain is $-17c < x < 17c$ and $-17c < y < 17c$ (where $c$ is the chord length of the wing), and a no-slip boundary condition is applied to the surface of the moving wing. The translational speed of the wing surface considered the speed of the boundary ($d(t)$ in Eq. (7)). The outer boundary is

![Fig. 9. Aerodynamic force coefficients during two cycles of hind wing flapping.](image)

![Fig. 10. Numerical results of the elytron flapping: vortex field contour (left) and pressure field contour (right).](image)

![Fig. 11. Aerodynamic force coefficients of the elytron flapping during two cycles.](image)
than that of the vertical force due to the relative orientation of the negative value. The augmentation in the horizontal force is larger when the vertical force increases and the horizontal force falls to a large area when the wing touches the high pressure region. Subsequently, the vortices are generated on the wing trailing edge as shown in the vortex field Fig. 9 presents the coefficients of the time-dependent aerodynamic forces. At the initial stage of the downstroke, the wing orientation is vertical; thus, the horizontal force is higher than the vertical force. From the beginning of the downstroke, a delayed stall occurs when the wing starts flapping impulsively downward from the rest position at an angle of attack larger than the stall angle. Large vortices then form at the leading edge and trailing edge, increasing both the vertical and horizontal forces. As shown in Fig. 7, the leading-edge vortex stays attached to the wing until $t/T = 0.25$. At this moment, the difference in pressure between the upper and lower surfaces is almost zero. Therefore, the hind wing of a Coleopteran insect can be classified as a normal hovering type even if its kinematics model has a negative stroke angle. The time-averaged values are $0.622$ for the horizontal force coefficient and $-0.209$ for the horizontal force coefficient. Here the negative mean value of the horizontal force coefficient is deemed to be a far-field boundary, so the normal traction is zero. We used a time step of $0.1$ ms, which is equivalent to $T/80$. As shown in Fig. 2, the structured mesh was generated in the whole domain with a clustering mesh around the wing. As a preliminary step, we examined the effect of the grid system with different numbers of grids, namely 80, 100, 120 and 160, along the periphery of the wing. Fig. 6 depicts the effect of number of the grid points on the accuracy of the solution. The vertical force coefficient approaches a convergent value after three periods when the number of the grid points exceeds 120. We therefore chose to use 120 grid points for following simulations.

3.2.1. Hind wing only

Figs. 7 and 8 show the vortex and pressure field distributions during one cycle of flapping, and Fig. 9 presents the coefficients of the time-dependent aerodynamic forces. At the initial stage of the downstroke, the wing orientation is vertical; thus, the horizontal force is higher than the vertical force. From the beginning of the downstroke, a delayed stall occurs when the wing starts flapping impulsively downward from the rest position at an angle of attack larger than the stall angle. Large vortices then form at the leading edge and trailing edge, increasing both the vertical and horizontal forces. As shown in Fig. 7, the leading-edge vortex stays attached to the wing until $t/T = 0.25$. At this moment, the difference in pressure between the upper and lower surfaces of the wing generates high horizontal and vertical forces. Towards the end of the downstroke, the wing moves upward with a high angle of attack. Subsequently, the vortex is fully detached from the wing, as shown in the vortex field at $t/T = 0.45$. Hence, the pressure difference between the upper and lower surfaces becomes small and, as shown in Fig. 9, both aerodynamic forces are reduced to zero.

During the transition period from the downstroke to the upstroke, the wing rotates clockwise and captures the vortices generated from the previous downstroke; at the same time, new vortices are generated on the wing trailing edge as shown in the vortex field at $t/T = 0.6$. In the pressure field at the same time step, the wing touches the high pressure region. Subsequently, the vertical force increases and the horizontal force falls to a large negative value. The augmentation in the horizontal force is larger than that of the vertical force due to the relative orientation of the wing towards the flow direction. The increment of these unsteady forces can be determined from the wing rotation or rotational circulation and from wake capture phenomena (Dickinson et al., 1999). At $t/T = 0.9$, vortex shedding from the wing edges can be observed at a high angle of attack. Therefore, the pressure difference between the upper and lower surfaces is almost zero and both forces become almost zero. As described previously, the hind wing achieves lift through the delayed stall, rotational circulation and wake capture. A positive vertical force appears to be generated during the upstroke as well as the downstroke. Reflecting typical aerodynamic characteristics of insect hovering, the maximum peaks of the upstroke and downstroke are similar (Wang, 2000a). Furthermore, the angle of attack is similar for the downstroke and the upstroke. The small stroke plane angle is observed like the normal hovering. Thus, the graph of the vertical force shows positive values for the hovering, whereas the graph of the horizontal force is quite symmetrical to a zero-axis. Consequently, the hind wing of a Coleopteran insect can be classified as a normal hovering type even if its kinematics model has a negative stroke angle. The time-averaged values are $0.622$ for the vertical force coefficient and $-0.209$ for the horizontal force coefficient. Here the negative mean value of the horizontal force means that Coleopteran insect is moving backwards and that is also observed in the free hovering flight experiment.

3.2.2. Elytron only

A computational simulation of an elytron flapping without a hind wing was also performed under the same conditions as the hind wing flapping. The elytron wing is modeled as a rigid camber shape. Because the elytron flapping synchronizes with the hind wing flapping, the elytron is also expected to generate some forces. Fig. 4 shows a case where the stroke plane amplitude of the elytron is only 0.75 times its chord length along the inclined stroke plane. In this case, it is necessary to quantify how much the elytron contributes to the force generation in hovering flight. Fig. 10 depicts the vortex and pressure fields around the elytron wing. The size of the vortex and the difference in pressure are much smaller than the corresponding values of the hind wing. As shown in Fig. 11, each half-stroke generates an almost equal portion of horizontal force and vertical force because the angle of attack is linearly changed in both the downstroke and the...
upstroke. The vortex and pressure fields seem to be inversely symmetrical to the center of the wing at $t/T = 0.175$ and at $t/T = 0.65$; the inversely symmetrical tendency causes equalities in the aerodynamic forces. From Fig. 11, the average coefficient values during one cycle are $0.001$ for the vertical and $0.005$ for the horizontal force, both much smaller than the corresponding values of the hind wing. Thus, the elytron aerodynamic forces in hovering flight make a negligible contribution to the overall aerodynamic forces of a Coleopteran insect. In the next section, we focus on how extensively the elytron affects the aerodynamic force of the hind wing in terms of wing–wing interaction.

### 3.2.3. Wing–wing interaction

To investigate the aerodynamic performance of the wing–wing interaction of the elytron and hind wing, we used two wing models in a single computational domain. Due to the complexity of the models, we used unstructured mesh; and the size of the element around the wing model was similar to the size of the structured mesh for the case of the hind wing only. The vortex and pressure distribution around both wings were captured at typical time step ($t/T$) values of $0.1$ and $0.75$, as shown in Fig. 12, which represent the time when the aerodynamic forces on the hind wing are different between the cases with and without the interaction. Fig. 13 plots the full aerodynamic forces of the hind wing and elytron, with and without any interaction. In hovering flight, the elytron has little effect on the aerodynamic forces of the hind wing because the small stroke plane amplitude and stroke plane put the focus of the forces on the hind wing. At $t/T = 0.1$, when the wings are close together in the early stage of the downstroke, the force value is small. The vortices near the leading edge of the hind wing are stronger than the corresponding values of the hind wing only, and the difference in pressure between the top and bottom lines of the hind wing is larger than that of the case with the hind wing only, as shown in the second column of Fig. 12. Hence, the two instantaneous aerodynamic forces are almost doubled. From the $t/T = 0.125$, the forces increase and the cases with and without interaction have similar results. At the middle of the upstroke,
$t/T = 0.75$, the vortex shedding is faster and stronger on the hind wing with the wing interaction than that of the hind wing only case and the instant forces are lessened. However, the overall average values of the forces during one stroke are approximate. Fig. 13 shows that, even though the forces on the elytron are negligible, the elytron clearly generates negative forces during the cycle except at the beginning of the downstroke. In hovering flight, there is a smaller discrepancy in the overall aerodynamics forces of the two wings with the wing interaction than the hind wing only case. However, role of the elytron may be significant in forward flight due to the wing kinematics, the camber of the curved shape, and the wing interaction with the incoming flow. The elytra may improve the vertical force for in forward flight.

### 3.3. Effect of the Reynolds number

The numerical simulation for the hind wing kinematics model of a Coleopteran insect was performed by varying the Reynolds number. For this simulation, we analyzed Reynolds numbers of 5000, 3141, 1000, 500, 157, 50, and 10. At lower Reynolds numbers, viscosity is the dominant factor of the numerical simulation (Kim and Choi, 2007; Wang, 2000b). The transition regime for a distinct pattern of aerodynamic force has been studied in depth at a very low Reynolds number (from 8 to 128) for tiny insects (Miller and Peskin, 2004). A Reynolds number of 50 indicates a transition phase; the forces in this phase are quite different from the above-mentioned ranges because the viscous forces become dominant. As shown in Fig. 14, when the Reynolds
number is 10, the force distribution is totally different from that of the other cases. This distinctive force distribution can be observed to a lesser extent with a Reynolds number of 157. The aerodynamic forces are very similar when the Reynolds numbers are greater than 500. The way the aerodynamic force varies when the Reynolds number is changed can be explained by the vortex shedding.

When the value of $t/T$ is 0.25 during a downstroke, as shown in the first row of Fig. 15, the leading edge vortex is detached from the wing faster at $Re=50$ than at $Re=3141$ due to the increase in the viscous property. Hence, as shown in Fig. 14, at $t/T=0.25$, there are different peaks of vertical and horizontal forces as the Reynolds number varies. Furthermore, as indicated in second row of Fig. 15, at $t/T=0.6$, the wake capture mechanism is not seen clearly for the case of $Re=50$. The wing rotates in reversal direction and does not capture the vortex generated from the previous downstroke due to slow movement of the vortex in high viscous (low $Re$) environment. Consequently, the temporary vertical force coefficient of the case of $Re=50$ is smaller than that of the others. As a result, we can conclude that aerodynamic performance is diminished with the low Reynolds number by degrading the typical unsteady mechanisms. On the other hand, as shown in Fig. 14, when the Reynolds number is higher than the natural value (3141), its effect on the aerodynamic performance is insignificant.

3.4. Effect of the flexible wing

To investigate flexible wing effect on the aerodynamic force, we performed another simulation with a chordwise flexible wing by using a Young’s modulus ($E$) of 1 GPa and a Poisson’s ratio ($\nu$) of 0.3. Fig. 16 shows the vortex distribution around the wing at the initial stage of the upstroke ($t/T=0.6$). Fig. 17 compares the flexible and rigid wing force distributions. The instantaneous horizontal force coefficient can be reduced significantly from $-2.8$ to $-2.2$ at $t/T=0.6$, whereas there is no significant difference in value for both forces at the other time steps. In general, the production of aerodynamic force decreases as the flexibility increases (Zhao et al., 2009). This result highlights the effect of a flexible insect wing in terms of its passive rotation or deformation during the transition period from a downstroke to an upstroke. In contrast with a rigid wing, the flexible wing gently touches the vortices generated in a previous downstroke, thereby minimizing any adverse force on the wing.

4. Conclusion

In this paper, the wing kinematics of a Coleopteran insect was modeled with the aid of a digital high-speed camera. The kinematic data were used in a 2-D numerical simulation to investigate the aerodynamic characteristics of the flapping elytron and hind wing, and to identify role of elytron, i.e., how the elytron–hind wing interaction affects aerodynamic performance. The computed aerodynamic force indicates that an effective vertical force is generated in both the downstroke and the upstroke. For an elytron that flaps along an inclined stroke, each half-stroke generates an almost equal vertical force and horizontal force but the total average force is much weaker than that of the hind wing. Our detailed investigation also confirms that the high viscosity that occurs with a low Reynolds number diminishes the vertical force and strengthens the horizontal force. In the case of hovering flight, the relatively small vertical or horizontal forces generated by the elytron suggest that the elytron makes no significant contribution to aerodynamic force during hovering flight. It is also confirmed that the flexibility of a wing in hovering flight plays a significant role in generating lift forces.

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