Development of Bird-like Micro Aerial Vehicle with Flapping and Feathering Wing Motions

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(Received October 24th, 2006)

To investigate the feasibility of a highly efficient flapping system capable of avian maneuvers, such as rapid takeoff, hover and gliding, a full scale bird-like (ornithopter) flapping-wing micro aerial vehicle (MAV) shaped and patterned after a typical pigeon (Columba livia) has been designed and constructed. Both numerical and experimental methods have been used in the development of this vehicle. This flapping-wing micro aerial vehicle utilizes both the flapping and feathering motions of an avian wing by employing a novel flapping-feathering mechanism, which has been synthesized and constructed so as to best describe the properly coordinated flapping and feathering wing motions at phase angle difference of 90° in a horizontal steady level flight condition. This design allows high flapping and feathering amplitudes and is configurable for asymmetric wing motions which are desirable in high-speed flapping flight and maneuvering. The preliminary results indicate its viability as a practical and an efficient flapping-wing micro aerial vehicle.

Key Words: Micro Aerial Vehicle, Flapping Wing, Flapping-Feathering Motion, Ornithopter

1. Introduction

The development of extremely small aerial robots or micro aerial vehicles (MAVs) of the same size and weight range as natural fliers has sparked renewed interest in flapping flight because of their unique capability to perform a wide array of missions such as over-the-hill reconnaissance and surveillance, targeting, tagging, bio-chemical sensing, and flying in a rarefied atmosphere, such as on Mars. With a size of approximately 15 cm in length, width or height and a flight speed of a few meters per second, a micro aerial vehicle (MAV) will fly at Reynolds number $10^4$–$10^5$, far lower than conventional aircraft ($10^6$). In this low Reynolds number flight regime, MAV aerodynamic behavior is different from that of larger, faster aircraft, because viscous forces are more significant when getting down to this size and air speed range. Despite recent remarkable achievements obtained with fixed and rotary Unmanned Aerial Vehicles (UAVs), their use in many tasks is still limited by maneuverability and size. To overcome these limitations, the extraordinary flight capabilities of birds and insects have inspired the design of extremely small aerial robots or MAVs with flapping wings mimicking real flying insects (entomopters) and birds (ornithopters). An aerial vehicle with this design is generally scalable up to a size on the order of few millimeters as can be observed in nature. Another major advantage to flapping-wing design relates to the minimum speed of the vehicle that allows longer target coverage and its ability to perform short takeoffs and landing. Provided with enough power and sophisticated control system, a vehicle with flapping wings could actually takeoff and land vertically. Although birds and aircraft enjoy similarity in some important geometrical quantities, the flapping-wing design and construction of present biomimicked MAVs are only moderately successful because of the mechanical and aerodynamic complexities inherent in flapping flight.

Based on several studies conducted on many different families of insects and birds, biologists and naturalists have provided kinematic descriptions of flapping wing motion and empirical correlations between flapping frequency, weight, wing span, and power requirements, while bio-fluid-dynamicists have explained the underlying physical phenomena both in the quasi-steady limit and in the fully unsteady flow regimes. Computational Fluid Dynamics (CFD) has been used recently to investigate the unsteady flow phenomena in oscillating wings to validate different aerodynamic models and to shed light on phenomena underlying flapping flight. For instance, Jones and Platzer calculated the inviscid flow for 2D airfoils in plunging and pitching motion in comparison with analytical results. Calculations of inviscid 3D flow around flapping wings are also available with respect to time-dependent forces in the works of Smith, and Vest and Katz, but results for mean thrust output and efficiency are rarely available. For the viscous flow around 2D and 3D wings, Navier-Stokes solutions have been presented by Isogai et al. and Isogai, respectively.

This paper presents the development of a bird-like flapping wing MAV with flapping and feathering wing motions. Numerical and experimental studies have been conducted on the flapping wing kinematics and aerodynamics, and on the mechanization and design requirements of this vehicle. An unsteady viscous flow simulation has been performed using a 3D Navier-Stokes code in investigating the effects of dynamic stall phenomenon on the propulsive efficiency, thrust and lift of the flapping wing being used. A novel two degrees-of-freedom (DOF) flapping-wing mechanism
utilizing both the flapping and feathering characteristics of a typical bird is also introduced.

2. Flapping Wing Motion

2.1. General flapping wing kinematics

In general, there are four DOF in each wing that are used to achieve flight in nature: flapping, lagging, feathering, and spanning. Flapping is an angular movement of the wing about an axis in the direction of flight. Lagging is an angular movement of the wing about a vertical axis, which effectively moves the wing forward and backward parallel to the body. Feathering is an angular movement about an axis in the wing which tilts the wing to change its angle of attack. Spanning is an expanding and contracting of the wingspan. These motions require a universal joint similar to the shoulder of a human, but not all flying animals implement all these motions. Most insects, for instance do not use spanning. Thus, flapping flight is possible with fewer combinations of these four DOF.

Flapping flight is actually possible with only one DOF by using “flapping” alone. Several studies have been made on flapping flight using this one DOF. Vest and Katz16) pointed out that a one DOF flapping MAV modeled after a typical pigeon (Columba livia) can develop sufficient thrust to propel itself in a steady forward flight. It is also proposed that the propulsive efficiency of a future MAV in a steady forward flight can be significantly improved by adding periodic twisting (feathering) during the flapping cycle.

Of the four DOF available in flapping flight in nature, it is the combination of flapping and feathering motions that makes the most significant contribution to lift and thrust production. Therefore, it is practical to utilize just two DOF in designing and building an effective bird-like MAV. Using these two degrees of freedom there are four important variables with respect to wing kinematics: (1) wing beat frequency, (2) wing beat amplitude, (3) wing feathering as a function of wing position, and (4) stroke plane angle. When properly coordinated, these motions can provide lift both during the downstroke, and the upstroke. The ability to generate lift on both strokes leads to the potential for hovering flight in insect-like (entomopter) and bird-like (ornithopter) MAVs.

2.2. Coupled flapping-feathering motion

As defined in Fig. 1, the vertical displacement of the arbitrary point on the upper/lower surfaces of the wing can be expressed as:

\[ z(x, y, t) = z_0(x, y) + f(x, y, t) \]  

(1)

where \( z_0 \) is the time-mean displacement of the upper/lower surfaces, and \( f \) is the displacement of the upper/lower surfaces from the time-mean displacement \( z_0 \). The term \( f(x, y, t) \) in Eq. (1) is given by:

\[ f(x, y, t) = (h_t + \theta_0 y) \sin(kt) \]

\[ - (a_t + b_0 y)(x - x_p(y)) \sin(kt + \phi) \]  

(2)

where \( k \) is the reduced frequency based on the root semi-chord \( b_t \) and is defined by \( k = (b_t \omega)/U \), where \( \omega \) is the circular frequency of the wing and \( U \) is the free-stream velocity. In Eqs. (1) and (2), all the physical quantities are nondimensionalized by \( b_t \). In Eq. (2), \( t \) is the dimensionless time, \( h_t \) is the amplitude of the flapping oscillation at the root station, \( \theta_0 \) is the amplitude of the flapping oscillation, and \( \alpha_t \) is the amplitude of the feathering oscillation at the root station. The amplitude of the feathering oscillation is assumed to increase linearly toward the tip station with the slope of \( b_\alpha \), \( x_p \) is the \( x \) coordinate of the feathering axis, and \( \phi \) is the phase-advance angle of the feathering motion ahead of the flapping motion. Aided by analysis of the flow around a 2D airfoil, the kinematics of the coupled flapping (plunging) and feathering (pitching) motion are well known as described in Figs. 2 and 3.

The reduced frequency is a comparison of the angular velocity and the flow speed and the measure of the degree of unsteadiness. As \( k \) increases, so does the flow unsteadiness. \( k = 0 \) corresponds to a rigid fixed-wing vehicle, while the normal cruising flight of a typical pigeon has \( k = 0.25 \). The reduced frequency, together with the dimensionless plunging amplitude \( (z_0/b_t) \), influences the angle of attack.

\[ \phi = \gamma + \alpha \]
(γ) caused by pure plunging, as shown in the figure and is given by:

\[ \gamma(t) = \tan^{-1}\left(\frac{-\dot{z}(t)}{U}\right) \]  

(3)

The maximum angle of attack through pure plunging for small values of \( k \) and \( z_t/b_t \) is approximately:

\[ \gamma \approx k z_t/b_t, \]

(4)

where

\[ \gamma \approx \tan^{-1}(\gamma) \]

The momentary effective angle of attack, \( \lambda = (\gamma + \alpha) \), can be enlarged or diminished depending on the phase shift \( \phi \) of the superimposed pitching motion. To ensure attached flow throughout the entire flapping cycle, \( \lambda \) must be kept below 12° to 15°.

2.3. Basic aerodynamics

A flapping wing generates lift and thrust mainly by virtue of the so-called Knoller-Betz effect\(^\text{17,18}^\) whereby the wing oscillations induce vertical lift and longitudinal thrust components of the aerodynamic force (the force normal to the direction of the free stream velocity relative to the flapping wing), and by the complex effects of the generated vortex structures that enable high lifting and propulsive properties. Lift and thrust generation can be increased by increasing the flapping amplitude or flapping frequency as long as the flow remains attached to the airfoil. The aerodynamic lift, drag, and thrust coefficients can be expressed as follows:

\[ C_L = \frac{L}{\frac{1}{2} \rho U^2 S}, \quad C_D = \frac{D}{\frac{1}{2} \rho U^2 S}, \quad C_T = \frac{T}{\frac{1}{2} \rho U^2 S}, \]

(5)

where \( L, D, T, U, S, \) and \( \rho \) are lift, drag, thrust, flight speed, wing planform area, and air density, respectively. In steady level flight, the lift force equals the body weight, \( W_g \), so the wing loading can be expressed as:

\[ L = W_g = \frac{1}{2} \rho U^2 S C_L \Rightarrow W_g/S = \frac{1}{2} \rho U^2 C_L. \]

(6)

The wing loading summarizes the opposing action between two classes of forces in flight: (1) the gravitational and inertial forces, and (2) the aerodynamic forces that are responsible for creating lift and thrust. The range of wing loading is limited by physical constraints. As an example, larger birds do not have high flapping frequency because their bones cannot withstand the stresses imposed by moving such a large inertial load.

2.4. Power muscle

Depending on the characteristics of the wings and body and flight speed, flapping-wing design requires some amount of power to remain aloft in still air. In birds, for the *pectoralis-major* muscle which is entirely responsible for the heavily loaded downstroke (15% of the total mass), the *supracoracoideus* muscle, which powers the upstroke, and the tail muscles (levator caudae and depressor caudae) take up about 20% of the animal’s total mass (Fig. 4).

For birds, Weis-Fogh\(^\text{20}^\) set the upper limit on sustained power generated per unit mass of muscle at 200 W per kg of muscle (compared with 15–20 W per kg of muscle for man). Given that up to 20% of birds total mass is flight muscle, the greatest sustainable specific power in flapping forward flight is 40 W/kg, with some possible reduction below that value as size increases. Pennycuick\(^\text{21}^\) suggested that the upper limit on mass may be about 12 kg, and that above this value the bird can no longer sustain the output needed for flapping flight.

The power requirement of an MAV depends on (1) weight of the vehicle, (2) flight speed, and (3) aerodynamic parameters (\( C_L/C_D \)). As MAV size reduces, the weight drops. However, the small physical size and low flight speed also result in substantially lower Reynolds number, which decreases \( C_L/C_D \). This degradation in aerodynamic performance means that a MAV cannot be designed simply based on the same concept as a conventional aircraft, otherwise it lacks the aerodynamic characteristics to remain airborne.

In steady level flight, the average power output is determined by production of average thrust and flight speed as:

\[ \bar{P}_{\text{out}} = \bar{T} U \]

(7)

The propulsive efficiency, \( \eta_p \), for one flapping cycle, is an essential parameter because it measures how well the input power, \( P_{\text{in}} \), is transformed to output power, \( P_{\text{out}} \), and is given by:

\[ \eta_p = \frac{P_{\text{out}}}{P_{\text{in}}}. \]

The following formulas given by Rayner and Gordon\(^\text{22}^\) for birds in a continuous vortex wake model make it possible to estimate the power-to-mass ratio either for birds, or for machines that can attain performance comparable to birds:

Maximum Range Speed,

\[ V_{\text{m}}(\text{m/s}) = 10.00M^0.413 S^{-0.553} \]

(9)

Mechanical Power at that Speed,

\[ P_{\text{mech}}(\text{W}) = 27.21M^{1.590} S^{-1.818} \]

(10)

Total Power,

\[ P_{\text{tot}}(\text{W}) = 114.61M^{1.145} S^{-1.225} \]

(11)
where $M = \text{mass (kg)}$, $B = \text{wingspan (m)}$, and $S = \text{wing planform area (m}^2\text{)}. The total power for flight in a bird is measured as the total rate of metabolic energy uptake $P_{\text{met}}$.

A sample calculation for a typical pigeon with the mass, wingspan, and wing planform listed in Table 1 shows that $V_{mr} = 11.02 \text{ m/s}$, $P_{mr} = 6.03 \text{ W}$, and $P_{\text{met}} = 15.15 \text{ W}$. Because a bird controls speed by varying its wingbeat kinematics, and the wingbeat frequency and amplitude are directly related to muscle contraction rate, and the muscle efficiency is related to muscle strain rate, it is difficult to predict the physiological efficiency because it varies with flight speed. However, these constraints on efficiency may not be important for a MAV if the actuator(s) responsible for wing movement can maintain efficiency while varying wing beat kinematics appropriately.

### 3. Numerical Method, Example, and Discussion

For a 3D wing, all the previous theoretical studies mostly based on the potential flow assumption. However, as we can see in flying birds, the amplitude of the flapping motion of the wing is very large (for example, the flapping angle of a pigeon is about $\pm 50^\circ$ as listed in Table 1) and that the induced angle of attack (due to the flapping motion of the wing) exceeds easily the stall angle.

To compute the unsteady viscous flow around a wing with coupled flapping and feathering described in Eq. (1), a 3D compressible Navier-Stokes (NS) code is used. The grid in the computation is a C-H type structured grid, 240 (chordwise) $\times$ 31 (normal to surfaces) $\times$ 19 (spanwise). In the computations, Mach number and Reynolds number are assumed to be 0.30 and $10^5$, respectively, and Baldwin and Lomax turbulence model is used. Air at standard atmospheric pressure and temperature is used, where $\rho = 1.225 \text{ kg/m}^3$ and $\nu = 1.46 \times 10^{-5} \text{ m}^2/\text{s}$.

As an example for this NS computation, a straight tapered wing for two different oscillation modes is used to show that the occurrence of flow separation reduces the propulsive efficiency and thrust considerably. Figure 5 shows the flow pattern (iso-vorticity distribution) at $kt = \pi$ where the maximum effective angle of attack induced by the pure flapping motion (without feathering) becomes $31^\circ$ at the 75% semispan station. The large-scale flow separation is highly visible from the 50% semispan station to the tip station. $\eta_T$ and $C_T$ for this case (pure flapping) are 0.111 and 0.0374, respectively. The second case shown in Fig. 6 is for a coupled flapping and feathering motion wherein

![Fig. 5. Flow pattern at $kt = \pi$ for pure flapping wing motion.](image)

![Fig. 6. Flow pattern at $kt = \pi$ for coupled flapping-feathering wing motion.](image)

![Fig. 7. Variations of thrust and rate of work (solid line indicates coupled flapping-feathering motion; dashed line indicates pure flapping motion).](image)

Table 1. Typical pigeon characteristics.

<table>
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<th>Characteristic</th>
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</tr>
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<tr>
<td>Aspect ratio</td>
<td>7.2</td>
</tr>
<tr>
<td>Flapping frequency</td>
<td>8 Hz</td>
</tr>
<tr>
<td>Wing span</td>
<td>0.66 m</td>
</tr>
<tr>
<td>Wing area</td>
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</tr>
<tr>
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</tr>
<tr>
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The maximum effective angle of attack at the 75% semispan station is about $11^\circ$. As can be seen, there is no large scale flow separation. $\eta_T$ and $C_T$ for this case are 0.619 and 0.106, respectively, and are considerably, higher than for the first case. Figure 7 shows the variations of thrust and rate of work for the two cases.

In the present study, this 3D compressible Navier-Stokes code is used to evaluate the unsteady viscous flow around the flapping pigeon wing shown in Fig. 8; the role of flow separation, especially the effect of dynamic stall on the propulsive efficiency, thrust, and lift of the flapping wing are investigated. There are two major reasons for using the pigeon wing in this research: (1) availability, and (2) because this species has been used by other investigators, either for experimentation (Pennycuick) or for theoretical analysis (Vest and Katz). The pigeon wing planform,
wing section, and geometrical twist distribution measured by Nachtigall and Wieser\(^{24}\) are used. The pitching amplitude value is taken at the 75% semi-span station. The data listed in Table 1 and the aerodynamic performance results obtained from the numerical simulations are used as inputs in the design and development of the pigeon-like MAV.

Numerical simulation showed that the propulsive efficiency, \(\eta_p = 0.42\), thrust coefficient \(C_T = 0.12\), and lift coefficient \(C_L = 0.72\). Vest and Katz\(^{26}\) computed same case using a panel method, obtaining \(\eta_p = 0.64\), thrust coefficient \(C_T = 0.13\), and lift coefficient \(C_L = 0.85\). In this study computations, large-scale flow separation is observed on the upper surface from the 70% semispan to the tip station at the instant of \(kt = \pi\) when the induced angle of attack becomes maximum. Since flow separation reduces propulsive efficiency considerably, the results obtained in this study seem quite reasonable compared to those obtained by Vest and Katz\(^{26}\) using the panel method. Figure 9 shows the variation of lift (\(L\)), thrust (\(T\)) and rate of work (\(W\)) during one oscillation cycle. Most of the lift and thrust are generated during the downstroke (\(kt = \pi/2 - 3\pi/2\)).

4. Wing Mechanization

4.1. Techniques for flapping flight maneuvering

For a bird-like MAV design to be more effective, it must use two sets of fully independent but identical flapping-feathering mechanisms driven by two independent but identical actuators. Aside from controlling the MAV by changing the angle of attack of the wings while gliding (by stopping and changing the positions of the motors), it can also be controlled by varying the speed of the individual wing, thus producing asymmetric turning forces, which is ideal for high-speed maneuvering. This flight control method is inherent in pigeons, which, unlike other birds, use downstroke velocity asymmetries rather than angle of attack or surface area asymmetries to produce the disparities in force needed for directional changes (Warrick et al.\(^{27}\)). To bank for example, a velocity (and hence, aerodynamic force) asymmetry is created early in the downstroke, and in the majority of cases, is then reversed at the end of the same downstroke, thus arresting the rolling angular momentum. That is, the wing on the outside of the turn is driven down by the pectoral muscle at a higher rate than the inside wing. Thus, a pigeon creates a precise average body position (e.g. bank angle) and flight path by producing a series of rapidly oscillating movements.

4.2. Flapping-feathering mechanism

The flapping motion of the wing is described by a planar four-bar mechanical linkage shown in Fig. 10, while the feathering motion is described by a five-bar linkage that can be highly approximated by an equivalent planar four-bar mechanism. These two mechanical linkages are interconnected to form a flapping-feathering mechanism as shown in Fig. 11 to produce a properly coordinated flapping and feathering motion of the wing in the entire flapping wing cycle for a constant drive input. The insertion of the extra link in the feathering mechanism (making it a five-bar mechanism) introduces additional DOF in the moving plane determined by the position of the rocker of the
The flapping and feathering mechanisms have been designed to have the same upstroke and downstroke period throughout the entire flapping cycle for a constant crank angular speed input. Figure 12 shows that the limiting positions of the rocker occur when the crank and the rocker are collinear as shown in both figures. In general, the time required for the rocker oscillation in one direction will be different for the other direction. The figure on the left side of Fig. 12 shows the general case where the crank moves through the angle \( \psi \) from \( A_1 \) to \( A_2 \) while the rocker moves from \( B_1 \) to \( B_2 \) through the angle \( \theta \). On the return stroke, the crank moves through the angle \( 360^\circ - \psi \) and the rocker moves from \( B_2 \) to \( B_1 \) through the same angle \( \theta \). The ratio of the times required for the forward and return motions of the rocker is called the time ratio. For a constant crank angular velocity, the ratio of the times for the forward and the reverse strokes of the rocker can be related directly to the angles as shown in both figures. It is evident that to have the same upstroke and downstroke periods, \( B_1 \) and \( B_2 \) must lie in a straight line (\( \alpha = 0 \), right-hand figure in Fig. 12) passing through \( O_2 \).

The linkage can now be synthesized by using a suitable method and applying the Grashof inequality (a necessary condition for the presence of a fully rotatable joint and that joint is always at one end of the shortest link). The flapping and feathering mechanisms are both of type Grashof inequality I (crank-rocker), where the crank (input), \( r_2 \), rotates for \( 360^\circ \), and the rocker (output), \( r_3 \), oscillates through an angle \( \theta_4 \) as shown in Fig. 10 to Fig. 13. Link \( r_3 \) is called the coupler and \( r_1 \) is the rigid frame link.

After the synthesis, the mechanism can now be analyzed for its kinematics.

The loop closure equation of the vector polygon in Fig. 13 is given by

\[
\vec{r}_2 + \vec{r}_3 = \vec{r}_p = \vec{r}_1 + \vec{r}_4.
\]  

By utilizing Euler’s equation in the above equation, the linkage instantaneous positions may now be solved using the following equations:

\[
\begin{align*}
\theta_4 &= 2 \tan^{-1} \left[ \frac{-B + \sigma \sqrt{B^2 - C^2} - A^2}{C - A} \right], \quad \sigma = \pm, \\
\theta_3 &= \tan^{-1} \left[ \frac{r_1 \sin \theta_1 + r_4 \sin \theta_4 - r_2 \sin \theta_2}{r_1 \cos \theta_1 + r_4 \cos \theta_4 - r_2 \cos \theta_2} \right],
\end{align*}
\]

where,

\[
\begin{align*}
A &= 2 r_1 r_4 \cos \theta_1 - 2 r_2 r_4 \cos \theta_2, \\
B &= 2 r_1 r_4 \sin \theta_1 - 2 r_2 r_4 \sin \theta_2, \\
C &= r_1^2 + r_2^2 + r_4^2 - r_3^2 - 2 r_1 r_2 (\cos \theta_1 \cos \theta_2 + \sin \theta_1 \sin \theta_2).
\end{align*}
\]

The velocity and acceleration equations can be developed by taking the first and second time derivatives of Eq. (14), as shown in Eqs. (16) and (17), respectively. Figure 14 shows the graph of the motion of the four-bar mechanical linkage described above with \( r_1 = 20, \ r_2 = 10, \ r_3 = 18.15, \ r_4 = 13.05, \ \theta_1 = 65.2^\circ \), and a flapping speed of 50.24 rad/sec (8 Hz). Again, the flapping wing is attached to the rocker (\( r_4 \)) of the flapping mechanism and to the rocker of the feathering mechanism.

\[
\begin{align*}
\begin{bmatrix}
-r_3 \sin \theta_3 & r_4 \sin \theta_4 \\
-r_3 \cos \theta_3 & r_4 \cos \theta_4
\end{bmatrix} \begin{bmatrix}
\dot{\theta}_3 \\
\dot{\theta}_4
\end{bmatrix} &= \begin{bmatrix}
r_2 \dot{\theta}_2 \sin \theta_2 \\
r_2 \dot{\theta}_2 \cos \theta_2
\end{bmatrix}, \\
\end{align*}
\]

\[
\begin{align*}
\begin{bmatrix}
-r_3 \sin \theta_3 & r_4 \sin \theta_4 \\
-r_3 \cos \theta_3 & r_4 \cos \theta_4
\end{bmatrix} \begin{bmatrix}
\ddot{\theta}_3 \\
\ddot{\theta}_4
\end{bmatrix} &= \begin{bmatrix}
r_2 \dot{\theta}_2 \sin \theta_2 + r_2 \dot{\theta}_2^2 \cos \theta_2 + r_3 \dot{\theta}_3^2 \cos \theta_3 - r_4 \dot{\theta}_4^2 \cos \theta_4 \\
r_2 \dot{\theta}_2 \cos \theta_2 - r_2 \dot{\theta}_2^2 \sin \theta_2 - r_3 \dot{\theta}_3^2 \sin \theta_3 + r_4 \dot{\theta}_4^2 \sin \theta_4
\end{bmatrix}.
\end{align*}
\]
4.3. Twin-motor configuration and flapping-wing control

The two identical sets of flapping-feathering mechanisms are connected to and driven by two identical Faulhaber™ coreless DC micromotors (with 17-W output per motor) via two identical speed reducers. The right-hand side motor rotates in the counterclockwise direction while the left-hand side motor rotates in the opposite direction. The speed reducer gear ratio is 16:1 and ensures sufficient torque transmission for the flapping-feathering mechanism to be able to move the wing over the design range.

One misleading assumption in analysis and synthesis of planar four-bar mechanisms is that the angular velocity of the crank is constant. When the mechanism is driven by an electric motor through a gearbox, a periodically changing behavior in crank angular speed is observed due to the changes in inertia effects during the rotation of rigid links forming the mechanism. Since the assumption of a constant crank speed is essential for design of the flapping-feathering mechanism to realize timing requirements, a controller is needed to reduce the angular speed fluctuations introduced by the inertia effects and the aerodynamic forces.

5. MAV Design and Construction

Using the values in Table 1 for typical pigeon characteristics in a steady level flight condition and the results from numerical simulations, the design point parameters for the flapping-wing MAV are estimated as mean thrust, $T = 0.5514$ N, mean lift, $L = 3.814$ N, and drag, $D = 0.331$ N. Also, a value of $C_D = 0.072$ is used in the computation of the drag coefficient of the pigeon’s wings. The required torque for each wing during its entire cycle should be constantly sustained by the driving motor. It is assumed here that each wing supports half the vehicle’s total mass and that the aerodynamic force is concentrated and acting at a distance of 0.25 m from the root of the wing. A suitable and efficient power transmission is therefore necessary so the driving motor effectively moves the wing at the desired kinematics. The required torque per wing is calculated to be 47.83 mN-m. The value of the average power needed to move the wings and to propel the vehicle in steady level flight conditions is quite close to that of the estimated total power given by Eq. (11). With integration of the navigational and control system, the power requirement eventually goes even higher, exceeding that of the value given by Eq. (11). Selection of a suitable drive and transmission system is a major consideration in the design for compactness and power sustainability.

The wings and the aerodynamic body fairing covering the flapping-feathering mechanism were shaped and patterned after a typical pigeon with characteristics listed in Table 1 and from Refs. 24) and 28). The wings are considered rigid and constructed from foamed polystyrene with spar insert. The pigeon-shaped aerodynamic fairing is basically made up of three parts (head, main body and tail) which were made separately and bonded together to form a pigeon-like aerodynamic covering for the mechanism. The schematic of the MAV model assembly is shown in Fig. 15 and the actual MAV is shown in Fig. 16. The MAV assembly is composed of three major components: (1) the flapping-feathering mechanism assembly, (2) the wings, and (3) the aerodynamic body fairing.

6. Preliminary Experiments

The MAV model was mounted in the Flutter Wind Tunnel at Kyushu University to determine the efficiency of the flapping-feathering mechanism and for experimentation on aerodynamic performance. Aerodynamic loads were measured by a six-component internal sting balance mounted inside the vehicle. This internal force balance was also constructed in accordance with the future measurements of the aerodynamic performance of the flapping-wing MAV being developed. Calibration of the balance was performed by loading with calibrated forces. The balance signals were evaluated as a “calibration matrix,” giving a set of equations for “signals as functions of loads.” An inverse version of this set of equations, “loads as functions of signals,” was then used to evaluate the balance signals recorded during experiments in the wind tunnel. The strain gage signals from the internal force balance were conditioned and recorded by a National Instruments DAQCard-6036E data acquisition card connected to a portable computer running LabVIEW 7.1 software as shown in Fig. 17.

As part of the first steps in development of the flapping wing control system, a Parallax™ Basic Stamp 2 IC micro-
controller and Motor Mind C are being used. The control system was tested and tuned by allowing the model to move and flap its wings with zero wind-tunnel speed at different flapping frequencies, and then at different wind tunnel speeds (only up to 10 m/s because of the wind tunnel speed limitation) corresponding to flapping frequencies at the same reduced frequency.

7. Summary, Conclusions, and Future Work

A working bird-like (ornithopter) MAV shaped and patterned after a typical pigeon and utilizing both flapping and feathering motions in its wings was successfully constructed. It is now awaiting comprehensive performance evaluation and testing. The flapping-feathering mechanism has shown promising results during preliminary experiments (Fig. 18). The mechanism properly simulated coordinated flapping and feathering motions in steady horizontal flight and maneuvering. The mechanism easily configurable to perform independent wing motions which are vital in high-speed, avian-like, flight and maneuvering.

Future works includes the evaluation of the aerodynamic performance of the flapping-wing MAV using more comprehensive wind-tunnel experiments and numerical simulations, as well as full integration of the control system currently being developed for flight testing.

References