Preliminary design of bionic flapping wing vehicle

M A Moelyadi\textsuperscript{1}, E Amalia\textsuperscript{1*}, A D Tanoto\textsuperscript{1}, L M Septiani\textsuperscript{1}, M Rafie\textsuperscript{2}, A S Perdana\textsuperscript{1}, and R Agung\textsuperscript{1}

\textsuperscript{1} Faculty of Mechanical and Aerospace Engineering, Bandung Institute of Technology, Jalan Ganesha No. 10 Bandung 40132, Indonesia

\textsuperscript{2} School of Electrical Engineering and Informatics, Bandung Institute of Technology, Jalan Ganesha No. 10 Bandung 40132, Indonesia

*Corresponding E-mail: ema@ftmd.itb.ac.id

Abstract. This paper deals with the preliminary design of bionic flapping wing vehicle. The design is driven by its requirement and objective namely the maximum weight should be less than 0.5 kg with 1.5 m wingspan. In the conceptual design, the wing planform, wing structures and system of flapping mechanism will be considered to find the initial configuration and then continued the sizing of the flapping vehicle. The analysis of designed flapping vehicle is increasingly complex due to firstly the generation of time-dependent aerodynamic forces and moments from unsteady flow around the flapping wing, secondly, flexible wing structure which generates higher thrust may cause a structure failure and thirdly, a flapping mechanism system generating differential flapping motion for the vehicle maneuver. The aerodynamic analysis for given flapping motion model is carried out using Computational Fluid Dynamics method based the solution of unsteady Reynold Averaged Navier-Stokes equations and the structure analysis is conducted with the input of aerodynamic loads using Finite Element method to find critical stresses that may cause a structure failure. As a solution of differential flapping two controlled servos are used. The architecture of electrical system is made to analysis of the distribution of data signal and power. The flight maneuver is achieved by changes in flapping frequency and sweeping angle. The selection of system components is performed by considering weight constraint. The flight maneuver is achieved by changes in flapping frequency and sweeping angle. The wing platform has elliptical shape with airfoil maximum camber of 6% chord at a quarter chord. The outer body and wing are made of foam laminated by glass fibre with the foam density of 0.045 g/cm\textsuperscript{3}. The horizontal tail is made of mylar film with density of 1.38 g/cm\textsuperscript{3} and its area of 168.3 cm\textsuperscript{2}. As simulated results, the amount of total lift is 4.18 Newton generated at 6 Hz flapping frequency.

Keywords: bionic flapping, aerodynamics analysis, flapping mechanism, electrical system

1. Introduction

The development of bionic flapping wing vehicle has been inspired by bird since the beginning of its development [1]. Before developing a bionic flapping wing vehicle, researchers were studying about many
aspects of bird-like flapping wings. For example, in [1] it is studied by using CFD about the thrust production of flapping wing for a bird-like wing with wing span 1.1 m and chord 0.6 m. The results are the thrust produced by the flapping wing for frequency of 1 Hz, 2 Hz, and 4 Hz. Reference [2] studied about the aerodynamics performance of bird flight with retracted wing to increase thrust produced by bird wing at various frequencies.

While, other researcher is reporting study of unsteady aerodynamics simulation of bird wing for various frequencies. Here RANS solver was used for simulation with quasi-steady and unsteady cases [3], and also other studied about endurance efficiency for various motion model of flapping bird wing which are pure flapping, pure flapping-retraction, and symmetrical pure flapping-pitching [4]. In those reports, CFD simulations were carried out to calculate endurance efficiency and the higher endurance efficiency is for the flapping-pitching motion which is about ten times the other motion models. For theoretical study about the drag of flapping wing, reference [5] gives a good approach of drag prediction.

After having good understanding about how birds fly with their wings, then the principle is to be applied to an unmanned aerial vehicle (UAV). Further study gives a comprehensive review about some bionic UAV that used flapping wing [6], where it has been chosen for the product from FESTO “SmartBird” as our model in developing bionic flapping wing vehicle in this study. In developing our bionic flapping wing vehicle, previous studies reported by others have been used as a base for knowledge-based development of bionic flapping wing vehicle reported in this study [1-4].

2. Design Process
Preliminary design of our bionic flapping wing vehicle was started by using FESTO’s “SmartBird” as a model. By referring to reference [6], we make a list of design requirement and objective (DRO) as presented in table 1. Although “SmartBird” is used as the main model, DRO is opened for some modification that might be needed in design process.

| Table 1. Design Requirement and Objective |
|-----------------------------------------|
| Span Length : 30 – 150 cm              |
| Maximum Weight : 0.4 kg               |
| Flight duration : min 5 s             |

Based on DRO in table 1, design process was conducted with steps as follows: 1. Conceptual Design and Sizing; 2. Analyses of Aerodynamics, Structure, and System of Flapping Mechanism 3. Design Results. First we design planform, flapping mechanism, and electronic system. Then, we were conducting CFD simulation based on our accumulated knowledge. From reference [1], a general planform shape could be determined. After the planform is determined, then CFD simulation with FSI (Fluid Structure Interaction) approach is carried out for calculating lift and thrust produced by the planform. This process is referring to reference [1] to [4], reference [7] and [8].

After we make sure that the lift and thrust is sufficient, then we design the flapping wing mechanism based on reference [9], [10], and [12] to [16]. We considered some alternatives on this flapping wing mechanism and finally choose to use two-servo mechanism. After that, electronic system was designed. Finally, a structural analysis was conducted by using Finite Element Method to check whether the structure fails or not.

2.1 Aerodynamic Analysis of designed bionic wing configuration

The design of Flapping wings consider two aspects as given in Figure 1, firstly time-dependent aerodynamics loads subjecting on the surface that is influenced by some motion parameters such as air speed, flapping frequency, flapping dihedral angle, pitching angle and airfoil shape, and secondly structure deformation of the wings due to elasticity of the wing structure. When it is assumed as a decouple problem then we may reduce some important parameters such as a rigid wing [17] and simple oscillating plate.
Figure 1. Important Aspects of Design of the Flapping Wing Vehicle

Those parameters provide effects lift and thrust over time. From the previous work we know that flapping frequency heavily affect the thrust. Too high or near a resonated fluid-structure frequency produce complex structural respond, therefore will destroy thrust generation, but too low it produces no thrust at all. Strouhal number consisting of parameters of span length, frequency, and freestream velocity affects all variable roughly the same. For one geometrical dimension there must be a range of Strouhal number in which flapping wing will behave well (producing high amount of average lift with some amount of average thrust left).

Dihedral angle mostly affects maximum value of lift and the pitching angle assist to increase thrust when down stroking and to reduce drag when up stroking. Both angles could have different values when down stroking and up stroking. On the other hand, the camber and thickness mainly affect lift generation which behaves accordingly to airfoil theory. The material properties determine the structure response whether it assist thrust production or not. More rigid the material is, more lift produces at the expense of thrust.

The bionic flapping wing configuration is initially obtained based on early literature [7] namely a designed wing like a dove bird wing, which has a 20cm semispan and a 15cm root chord wing (see figure 2). In order to provide adequate aerodynamic lift to carry the target weight, the wing is modified by enlarging its span and area. The elliptic wing shape is used to minimize aerodynamic drag, so that the required power for driving the wing is lower and the battery weight and servo size can be reduced. The modification is done by taking the same dimensionless Strouhal number to maintain aerodynamic performance of the flapping wing without much change [9]. An iterative approximation to determine the size of the wing planform is as shown in flowchart of Figure 3.
\[ W_{target} = \rho \cdot V_1^2 \cdot C_l \cdot \text{semispan} \cdot \text{chord}. \]

\[ C_l \text{ assumed to be constant as long as Strouhal number is constant} \]

\[ Str = \text{frequency} \cdot \text{amplitude} / V_{\text{stream}} \]

\[ \text{Amplitude} = k \cdot \text{semispan} \cdot \sin(\text{max dihedral angle}) \]

**Figure 3.** Iterative Approximation for obtaining flapping wing Planform

The curvatures of the leading and trailing edges are made using Ellipse equation where the semi-major axis is the wing semispan and the semi-minor axis is starting from mean aerodynamic chord (MAC) to edge (either trailing or leading). The distribution of wing section along the spanwise is carried out with a sinus function distribution which is denser to the direction of the wing tip. The line of aerodynamic center of 25% of the chords is kept a straight for allocating the wing spar and the leading edge and trailing edge lines have the distances from the aerodynamic center with the ratio of 1:3 as shown in the figure 4.

This is to make the maximum chamber be always at 25% of the chords throughout the span. Because this wing will take a form as a thin shell wing, so this planform will take a chambered plate as a baseline instead of an airfoil. The important parameters that can be adjusted to obtain the geometry of the flapping wing are semispan, root chord, and maximum chamber. Table 2 shows the resulted geometry planform for the UAV Flapping wing and the flapping motion condition is given in Table 3.
Table 2. Geometry of Planform of the Flapping Wing

|            |            |
|------------|------------|
| Semispan   | 75 cm      |
| Root Chord | 30 cm      |
| Thickness  | 2 mm       |
| Max chamber| 6%         |

Table 3. Flying Conditions of the Flapping Wing for Simulation

|               |            |
|---------------|------------|
| $V_{body}$    | 10 mph     |
| Frequency     | 4.5.6 Hz   |
| $W_{target}$  | about 200 grams. |
| Total max dihedral angle | 60 degree |

This assumption has a drawback because even though the Strouhal number is kept constant (which is an important parameter in periodic unsteady flow), there is a very large change in the aspect ratio value, from 2.66 to 5 and there is a minor change in the Reynolds number.

2.1.2 Aerodynamic Analysis of Flapping wing

2.1.2.1 Governing equation of RANS, Turbulence Model and FSI Coupling

Fluid and structure interaction is a quite complicated involving both structural dynamics and fluid dynamics. They provide an influence each other. The changes in structure affect the surrounding fluid and the fluid flow producing a pressure on the body surface transferring to the structure. The equation for motion of the continuum body of the structure is as shown in equation (1).

$$\nabla^T \sigma_s + b_s = \rho_s \frac{\partial^2 u_s}{\partial t^2}$$  \hspace{1cm} (1)

where $\sigma_s$ is the diagonal value of the stress tensor in the structural material, $b_s$ is the body force (in this case there is only gravitational force), and $u_s$ is the location of the structural elements themselves.

For this case the fluid is assumed to be incompressible flow so that there is no coupling between the mass and momentum conservation equations with the energy equation as in equation (2). This is done by performing a simulation on CFX using the Air at 25°C option. So that the Navier stokes equation will be coupled with the remaining structure.

$$\nabla \cdot \vec{V} = 0$$

$$\rho \frac{\partial \vec{V}}{\partial t} + \rho \left( \vec{V} \cdot \nabla \right) \vec{V} = -\nabla p + \mu \nabla^2 \vec{V} + \rho \vec{g}$$  \hspace{1cm} (2)

Equation above also supplemented with general fluid boundary conditions such as no slip conditions on the walls, inlet conditions and surroundings. Initial conditions must also be determined in advance. Then the equation that combines the two systems is to equalize the fluid velocity with the structure on the wall (specifically no slip condition) and iteration between displacement and force.

The structure will accept the wall stress tensor and process it into displacement and the displacement will become a new boundary condition for the fluid to be analysed to produce a wall stress tensor (Cauchy stress tensor). In analytic equations the above must be done simultaneously. In CFD / CSD this will be done until it reaches convergence in each timestep as shown in Figures 5 and 6.
2.1.2.2 Simulation of Flapping wing

The simulations are carried out with Ansys CFX and Ansys Transient Structural through the coupling system between fluid and structure analysis as shown in Figure 5 and the computational domain is as shown in Figure 7. The simulations are done in a half-symmetrical model to save computational resources. For the structure model, a polyfoam material with density is 50g / cm3 is used obtained from references [9]. Elasticity is assumed to be an isotropic material with a modulus Young value of 3250 MPa and a Poisson ratio of 0.32.

The Movement are assigned at 25% chords assuming the line stretches across 25% of the chords (i.e. none other than the spars) remains rigid. The ratio of the maximum flap up and flap down is 2: 3. This value is taken from statistical data which have the max flap-down is greater than the flap-up and the ratio is quite significant but not too extreme.

![Figure 5. External CFD-CSD Coupled Simulation](image)

![Figure 6. Equations that used in CFD/CSD Coupling System](image)

![Figure 7. Fluid Computational Domain](image)
2.2 Structure of Bionic Flapping Wing

2.2.1 Structure Design of Bionic Flapping Wing

The design of flapping wing structures considers critical loads that may be occurred in several components including wings, supporting part and front fuselage. For the flapping wings, the cyclic aerodynamic loads subject to the wing surface. The loads are then transferred to the wing spar which is connected to the flapping mechanism devices such as joiners and servos. The spar should be designed to have a shape and size for maintaining bending moment and torsion. Figures 8 and 9 show the structure of wing and the structure of spar and joiner, respectively.

![Figure 8. Structure of wing and fuselage](image)

![Figure 9. Flapping Wing’s Servo-Spar Joint](image)

Next, the fuselage is designed to have a streamline shape with the rounded nose shape and to have a minimum weight. The fuselage nose may be subjected to the stagnation air load that may be critical causing the deformation of surface nose as shown in Figure 10. Inside the fuselage there is a main frame to support all electronic components including servo and the joint of the tail. This main frame may be also critical due transferring loads from the servos and the tail joint. In order to reduce its weight, the structure of the main frame is made some holes as depicted in figure 11.

![Figure 10. Flapping Wing’s Body](image)
2.2.2 Structural Analyses with Finite Element

The critical load on flapping wing structure occurs on wing spar. This is due to the aerodynamic load transferred to only one spar and connected to servo. For structure simulation, the model is developed and analyzed using finite element ABAQUS software with the first step is how to distribute loads in the spar. The lift distributing along spar is applied as uniform pressure on the bottom wing skin. This is to check if the designed spar is fail due to the bending moment of the lift distribution from wing skin.

The main materials used for flapping wing vehicle are carbon fiber and polyfoam. The structure materials are used as follows: carbon rod for the spar, carbon sheet for the servo-spar joint, polyurethane for wing, and polycarbonate for servo horn. The mechanical properties are shown in Table 4. Two different size of diameter of carbon rod are compared namely, 4 mm and 6 mm.

Table 4. Mechanical properties of carbon rod, carbon sheet, polyurethane, and polycarbonate

| Material                        | Parameter            | Unit | Value |
|---------------------------------|----------------------|------|-------|
| Carbon/Epoxy Composite Rod      | Longitudinal modulus | GPa  | 140   |
|                                 | Transverse modulus   | GPa  | 10    |
|                                 | Poisson’s ratio      | -    | 0.3   |
|                                 | Shear modulus        | GPa  | 5     |
| Carbon/Epoxy Composite Sheet    | Longitudinal modulus | GPa  | 70    |
|                                 | Transverse modulus   | GPa  | 70    |
|                                 | Poisson’s ratio      | -    | 0.1   |
|                                 | Shear modulus        | GPa  | 5     |
| Polyurethane                    | Modulus              | GPa  | 3.45  |
|                                 | Poisson’s ratio      | -    | 0.3   |
| Polycarbonate                   | Modulus              | GPa  | 2.48  |
|                                 | Poisson’s ratio      | -    | 0.38  |

2.3 Design of System of Flapping Wing Mechanism

2.3.1 Differential Flapping Motion

Differential flapping motion is preferred than BLDC (Brushless DC Motor) for driving flapping mechanism, since its compactness and simplicity in term of mechanical parts. Its simplicity is achieved by two servos configuration. Reducing number of parts to conduct in-flight maneuver will reduce overall AUW (All Up Weight) of the vehicle. Two servos are being used to conduct differential flapping motion.

Differential motion is being used to control frequency and center angular position of each servo independently. The control of servo movement will be programmed via an MCU (Microcontroller Unit). There are several proven examples of previous differential flapping wing vehicle, including: Robo Raven of University of Maryland and University of Southern California [6], and eMotionButterflies of Festo. Designed differential flapping motion is pictured as shown in Figure 12.
2.3.2 Design of Wing Mechanism
The servo is selected as a part of flapping mechanism to receive transferred load and driven the movement of the wing directly without any mechanical gear addition. However, it still need an additional part to link the servo’s gear with the wing’s spar. The critical thing that will be faced is the joint should be design properly to the complex form of the servo’s gear. To overcome this problem, the selection of 3D printed material and great design approximation should be conducted carefully.

2.3.3 Electric Components
This flapping wing vehicle is intentioned to have two main features, surveillance and autonomous flight. A FPV (First-Person View) camera is used for surveillance and GNSS (Global Navigation Satellite System) is used to determine geospatial position of vehicle. Figure 13 shows a diagram of power and data lines for integrating power and signal process of all electronic components of the bionic flapping wing. The requirement for electronic component selection is component weight with the maximum limit weight is 0.1 kg. The list of all used electronic components and each component weight data are given in Table 6.

![Figure 12. Stages of Differential Flapping Wing Motion](image)

![Figure 13. Power and Data Lines](image)
2.3.3.1 Differential Flapping Control

Differential flapping control act simultaneously as propulsion sub-system and surface control. It is done by creating certain output signal mixing for flapping motion of two-independent servos. The generation of motion from differential flapping control covers from: thru st, lift, roll, yaw, rising-lowering, to gliding. Designed output signal mixing is shown in Figure 14.

![Figure 14. Differential Flapping Control](image)

The output signal mixing is produced by outcoming signal post-processing from Flight Controller Unit (FCU) into Microcontroller Unit (MCU). The MCU modifies outcoming PWM signal from FCU into sinusoidal PWM signal to drive servo as flapping mechanism. A sweep angle correction is utilized to correct current servo position when exceeding determined minimum or maximum position. The exceeding position is as a result of lagging sequence of flapping command relative to signal mixing process. The reset state option is functioned for two purposes, first to reset previous mixing state, second to switch gliding mode when throttle input is below minimum threshold value.

3. Results and Discussions

3.1 The Bionic Flapping Wing Vehicle

The final design had made some change, specifically on the wing camber design due to achieve desired lift and thrust force. The final design of tail mechanism is quite simple, without any requirement to perform yawing then it was fixed on a particular angle of attack due to create some forces to make it has great longitudinal stability performance. Figure 15 shows the final design of the model.

![Figure 15. The Model of Flapping Wing Vehicle’s CAD](image)

3.2 CFD/CSD Simulation Results

Figure 16 shows the drag/thrust versus time graph and Figure 17 shows the lift versus time graph from the simulation as explained in the above section.
Figure 16. Drag/Thrust versus Time of the Flapping Wing Vehicle

Figure 17. Lift Versus Time of the Flapping Wing Vehicle

There is some numerical initialization error, so we are ignoring them. And then we do average per cycle, and because each simulation has different frequency and should be average based its own period. Table 5 shows the summary of simulation results for the flapping wing vehicle.

| Average drag/thrust(N) | Average Lift (N) | Average motor torque (Nm) |
|------------------------|-----------------|--------------------------|
| 4 hz                   | 4.55E-02 (drag) | 1.24E+00                 | 5.28E-01 |
| 5hz                    | 3.87E-02 (thrust)| 1.41E+00                 | 5.96E-01 |
| 6hz                    | 2.78E-01 (thrust)| 2.09E+00                 | 8.88E-01 |
3.3 Electric Components

Table 6 shows the electric components and weight that is used in the bionic flapping wing vehicle as explained in paragraph 2.3.3. Electric components is chosen to fulfill system requirement based on preceding simulation and further calculation.

The fundamental parts of flapping wing systems are propulsion-control servo and servo driver. KST MS320 as servo, capable to produce 5.50 kg.cm of torque. KST MS320 is able to produce flapping frequency 6.25 Hz. Teensy 3.2 as servo driver, is preferred because availability of interrupt pins across all digital pins. Interrupt pins are used to read/write PWM. The remaining components are chosen with performance and weight consideration. In total, it will be 94.6 gr of electric components weight. Figure 18 shows main frame with component assembled.

| Type                   | Name               | Gross Weight (gr) |
|------------------------|--------------------|-------------------|
| Propulsion-control servo | KST MS320          | 41.6              |
| Servo driver           | Teensy 3.2         | 3                 |
| Flight controller unit | Matek F722 SEF7    | 39                |
| Receiver               | Frsky XM+          | 1.6               |
| FPV camera All-In-One (AIO) | Caddx Firefly  | 4.1               |
| GNSS unit              | Matek SAM WorQ     | 7                 |
| Battery                | Emax Tinyhawk 5 300mAh | 15.3              |
| Cable and connector    | Various            | 8.2               |

Table 6. Electric Components of Flapping Wing Systems

Figure 18. Main frame with component assembled (a) Right side (b) Left side
### 3.4 Finite Element Result
After conducting the numerical simulation of this wing structure, the result shows some element which have high stress value. The element with the high stress value will be more tended to experience failure due to the given load. By comparing the 2 different diameters (4mm and 6mm), the Tsai-Wu Failure Criterion conducted to check either the structure will fail or not. Table 7 will show the Tsai-Wu Failure Criterion of the finite element analysis.

| Table 7. Tsai-Wu Failure Criterion Calculation |
|------------------------------------------------|
| Diameter 6 mm | Diameter = 4 mm |
| \( \sigma_1 \) | 432.716 MPa | \( \sigma_1 \) | 1180 MPa |
| \( \sigma_2 \) | 9.184 MPa | \( \sigma_2 \) | 13.644 MPa |
| \( \tau_{12} \) | 33.884 MPa | \( \tau_{12} \) | 78.88 MPa |
| \( X_T \) | 1900 MPa | \( X_T \) | 1900 MPa |
| \( X_C \) | 1300 MPa | \( X_C \) | 1300 MPa |
| \( Y_T \) | 50 MPa | \( Y_T \) | 50 MPa |
| \( Y_C \) | 250 MPa | \( Y_C \) | 250 MPa |
| \( S \) | 70 MPa | \( S \) | 70 MPa |
| \( F_1 \) | 0.001296 MPa\(^{-1}\) | \( F_1 \) | 0.001296 MPa\(^{-1}\) |
| \( F_2 \) | 0.024 MPa\(^{-1}\) | \( F_2 \) | 0.024 MPa\(^{-1}\) |
| \( F_{11} \) | -4E-07 MPa\(^{-2}\) | \( F_{11} \) | -4E-07 MPa\(^{-2}\) |
| \( F_{22} \) | -0.000008 MPa\(^{-2}\) | \( F_{22} \) | -0.000008 MPa\(^{-2}\) |
| \( F_{66} \) | 0.000204 MPa\(^{-2}\) | \( F_{66} \) | 0.000204 MPa\(^{-2}\) |
| Tsai-Wu | 0.934385 | Tsai-Wu | 2.553909 |

The Tsai-Wu Failure Criterion is satisfied with the composite material that was used in this spar and joint of wing in this vehicle and it is also satisfied with the bending phenomenon which is become the boundary condition of the Finite Element Analysis. The Tsai-Wu value should be less or same as 1 to ensure the structure will not experience any failure. Hence, the Table 7 shows that the structure which has larger diameter will be safe due to the inertia of the structure is larger and could stand with the given load. The definition of \( \sigma_1 \), \( \sigma_2 \), and \( \tau_{12} \) are the maximum stress in x direction, the maximum stress in y direction, and the maximum shear stress in xy plane. All of this stress value is obtained by Finite Element Analysis which is already described in previous section.

### 4. Conclusion
A model of bionic flapping wing vehicle has been designed with span length of 1.5 m and with flapping mechanism using 2-servo. It produced totally 4.18 N generated at 6Hz flapping frequency that has been fulfilled the requirement of the flapping wing. The structure of wing spar has been analyzed using finite element and the failure criteria of Tsai-Wu showing it remain safe for the given loads.

### References
[1] M. A. Moelyadi, D. A. Priyanto and G. Sachs, Simulation of Flexible Flapping Wing Bird in Producing Thrust, Journal of Unmanned System Technology, Vol. 2, No.2, September, 2014, pp. 62-69.
[2] M. A. Moelyadi, F. Rhamadiansyah and G. Sachs, Simulation of Aerodynamics of bird wing retraction, 9th International Conference on Intelligent Unmanned Systems 2013 (ICIUS 2013) Jaipur, India, 25-27 September 2013.
[3] M. A. Moelyadi, H. A. Putra and G. Sachs, Unsteady aerodynamics of Flapping Wing of a Bird, ITB Journal of Engineering Science, April 2013.
[4] R. Julistina and M. A. Moelyadi, CFD Based Prediction of Endurance Efficiency for Various Motion Models of Flapping Bird Flight, International Conference on 14th Intelligent Unmanned Systems 2018 (ICIUS 2018), Jeju, South Korea, 20-23 August. 2018
[5] Sachs G., Aerodynamics Cost of Flapping, Journal of Bionic Engineering, 12 (2015), 61-69.
[6] Chen C., Zhang T. (2019) A Review of Design and Fabrication of the Bionic Flapping Wing Micro Air Vehicles. Micromachines.
[7] Namhun Lee et al. (2018) “Effect of flexibility on flapping wing characteristics in hover and forward flight” in Elsevier.
[8] Alex E.H., et al. 2017. Characterizing and Modeling The Enhancement of Lift and Payload Capacity Resulting from Thrust Augmentation in a Propeller-Assisted Flapping Wing Air Vehicle. International Journal of Micro Air Vehicles.
[9] Mohd Firdaus Bin Abas (2016) “Flapping wing micro-aerial-vehicle: Kinematics, membranes, and flapping mechanisms of ornithopter and insect flight” in CJA at CSAA.
[10] Sutthiphone S., Woei-Leong C. 2015. Ornithopter Type Flapping Wings for Autonomous Micro Air Vehicles. Aerospace 2015.
[11] Chen, C., & Zhang, T. (2019). A Review of Design and Fabrication of the Bionic Flapping Wing Micro Air Vehicles. Micromachines, 4.
[12] Jackowski, Z. J. (2009). Design and Construction of an Autonomous Ornithopter. Boston: MASSACHUSETTS INSTITUTE OF TECHNOLOGY.
[13] Kim, D. K., & Han, J. H. (2006). Smart Flapping Wing Using Macro-Fiber Composite Actuators. In Y. Matsuzaki (Ed.), SPIE, 6166-6174, pp. 1-9. San Diego, California. doi:http://dx.doi.org/10.1117/12.658117
[14] Send, W., & al, e. (2012). Artificial hinged-wing bird with active torsion and partially linear kinematics. International Congress of the Aeronautical Sciences, 5.
[15] Srigarom, S., & Chan, W.-L. (2015). Ornithopter Type Flapping Wings for Autonomous Micro Air Vehicles. aerospace.
[16] Wang, P. L., & McCarthy, J. M. (2018, April). Design of a Flapping Wing Mechanism to Coordinate Both Wing Swing and Wing Pitch. Journal of Mechanisms and Robotics, 10, 1-6.
[17] Tantono, A.D.,(2019), Preliminary Wing Mechanism Design and CFD Analysis of Flapping Wing Mini Unmanned Aerial Vehicle, Bachelor Final Project, Bandung Institute of Technology.