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ANALISIS KINERJA SAYAP ORNITHOPTER SEPERTI-BURUNG SEDERHANA

PERFORMANCE ANALYSIS OF A SIMPLE BIRD-LIKE ORNITHOPTER'S WINGS

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Abstrak
Ornithopter atau sayap mengepak adalah robot yang menyerupai mekanisme sayap burung, serangga, atau kelelawar. Penerapan UAV jenis ini mulai dari fotografi hingga militer. Pokok bahasan penelitian ini adalah perancangan dan konstruksi sistem mekanik sayap ornithopter dengan sistem kepakan sayap double-joint. Kebaruan yang disampaikan dalam penelitian ini adalah bahan yang digunakan untuk membuat sayap ornithopter yaitu batang karbon untuk kerangka dan plastik untuk sayap. Tujuannya adalah untuk mengetahui kinerja aerodinamis sayap dan seluruh ornithopter. Hasil penelitian menunjukkan bahwa untuk sayap tunggal, nilai C_L/C_D tergolong tinggi. Namun desain ornithopter harus diperbaiki agar gaya dorongnya lebih tinggi dari gaya drag. Selain itu, kecepatan mulai meningkat secara stabil pada throttle 33,3%. Selanjutnya pada ornithopter ditemukan gaya angkat yang lebih besar dibandingkan gaya turun, sehingga secara teori robot dapat terbang. Lift terbesar terjadi pada nilai frekuensi 0,88 dan 0,97.
Kata Kunci: Ornithopter, Kepakan sayap, Gaya angkat, Gaya hambat, Sayap

Abstract
An ornithopter or flapping-wing is a robot that resembles the wings' mechanics of birds, insects or bats. The application of this type of UAV ranges from photography to the military. This study's main discussion is designing and constructing the ornithopter wing mechanical system with a double-joint wing flapping system. The novelty submitted in this study was the material used to construct the ornithopter wing, namely rod carbon for the skeleton and plastic for the wing. The aim was to discover the aerodynamic performance of the wing and the whole ornithopter. The study results showed that for single wing, the value of C_L/C_D *was high. However, the ornithopter design should be improved to get the thrust force higher than drag force. In addition, the velocity starts to increase stably at throttle 33.3%. Furthermore, for the ornithopter, it was found that the lift force was greater than the down force, so that, theoretically, the robot could fly. The largest lift occurred when the frequency values were 0.88 and 0.97.*
Keywords: *Ornithopter, Flapping-wing, Lift force, Drag force, Wings*

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INTRODUCTION

An ornithopter or flapping-wing is a flying object that adopting the flapping mechanism of birds, insects, and bats' wings. Flapping-wing is a type of UAV, besides fixed-wing and rotary-wing[1]. The flapping-wings produce lift and thrust force for the object to fly[2]. The Newton's third law of motion and Bernoulli's principle are the basic concept of developing ornithopters[3].

The theory of ornithopter structure had been pioneered by Abbas bin Firnas in the 9th century. The invention has been inspired many researchers to develop the modern flight technology. In the 1480s, Leonardo Da Vinci also studied and designed the ornithopter, which never been built by the designer. John Lichtenburg then built this Da Vinci's ornithopter design. In 1858, the Pierre Jullien model was estimated to have flown 40 meters. Then in 1870, Gustave Trouve's model floated a distance of 70 meters in a demonstration for the French Academy of Sciences.

Mechanism of the flapping flight surely has the higher complexity compared to the fixed-wing flight. However, flapping-wing perform more efficient energy utilization and lower cost. Therefore, along with technological developments, the development of ornithopters is also growing rapidly. This is proven by the increasingly efficient dimensions and mass of the ornithopter which is getting smaller until it reaches a unit weight of grams. The researchers succeeded in creating a 60 mg insect robot, which could generate sufficient lift force to take off vertically. To achieve this, the researchers utilized Micro Intelligent Composites (SCM)[4].

Researchers have also conducted some other studies to improve the ornithopter structure, efficiency, and other parameters. Sah and Pramanik[5] analyzed the prototype flapping-wing to get the insight into the dynamics of vehicle and the control of its flapping-wing mechanism. Additionally, experiments were conducted to examine the drag and lift forces acting on the flapping-wing membrane under different wind velocities and angles of attack. Faux et al[6] studied about the development of the elastic structure of artificial wings to enhance their dynamic performance in mimicking the movement patterns of insect wings. The bio inspired kinematics relies on the fundamental idea of utilizing the resonant characteristics of the wing's structure to integrate the movements of two vibration modes, namely flapping and twisting, with a phase shift of 90 degrees. Nian et al[7] investigated the implementation of flexible and asymmetrically deformable structures in flapping-wings. By introducing passive deformation, the wings exhibit enhanced aerodynamic performance, generating increased lift and reduced drag during flight. Widhiarini et al[8] conducted research which aimed to create a highly maneuverable and agile MAV capable of autonomous flight control. A flapping-wing micro air vehicle (FMAV) was created, mimicking bird flight with its flapping and twisting-wing drive system. Huang[9] conducted research to improve the modeling accuracy and validate the drone's performance through comprehensive testing. The results of the study demonstrate the successful development of a biomimetic flapping-wing drone with improved modeling accuracy. Lee[10] studied the optimization of the experimental design for a flapping-wing and the creation of a flapping mechanism using noncircular gears. The objective of the experiment was to improve the propulsive efficiency of a flapping-wing micro air vehicle (FWMAV). Bie et al[11] designed tailless flapping-wing UAV which was inspired by bat. The design was based on large flying fix biological data. Dorlikar and Pardeshi[12] investigated the mechanism synthesis of new flapping-wing to be applied in biomimetic aerial vehicles. Qin et al[13] conducted research on the control mechanisms of wingtip vortices generated during flapping. To achieve this, a flapping-wing model was developed, featuring two-jointed arms, which closely emulated the flapping motion observed in geese. Chen et al[14] proposed an analytical model aimed at providing a rapid assessment of the aerodynamic performance and passive deformation experienced by flexible flapping-wings. Abas et al[15] conducted a crucial advancement in Micro Aerial Vehicle (MAV) research, particularly focusing on kinematics, membranes, and flapping mechanisms observed in various organisms ranging from small birds to large insects, all operating within the transition and low Reynolds number regimes. Mishra et al[16] designed and developed a Micro Air Vehicle (MAV) with a flapping-wing design, inspired from nature. Its flight was controlled using micro-scale integrated on-board electronic circuits and communication devices.

There are still many challenges remain in developing the ornithopter. One of the challenges is designing and constructing the ideal ornithopter truss. The main discussion of this study is design and construct the ornithopter wing mechanical system with a double-joint wing flapping system (articulation). The novelty submitted in this study was the material used to construct the ornithopter wing, namely rod carbon for the skeleton and plastic for the wing. The aims were to discover the aerodynamics performance of the wing and the whole ornithopter.

MATERIAL AND METHODS

System Design

Figure. 1 shows the block diagram of the system, which generally represents the work principle of the ornithopter of this study. The blue dotted box represents the wing work system, while the red dotted box represents the steering system and altitude control using sonar sensors.

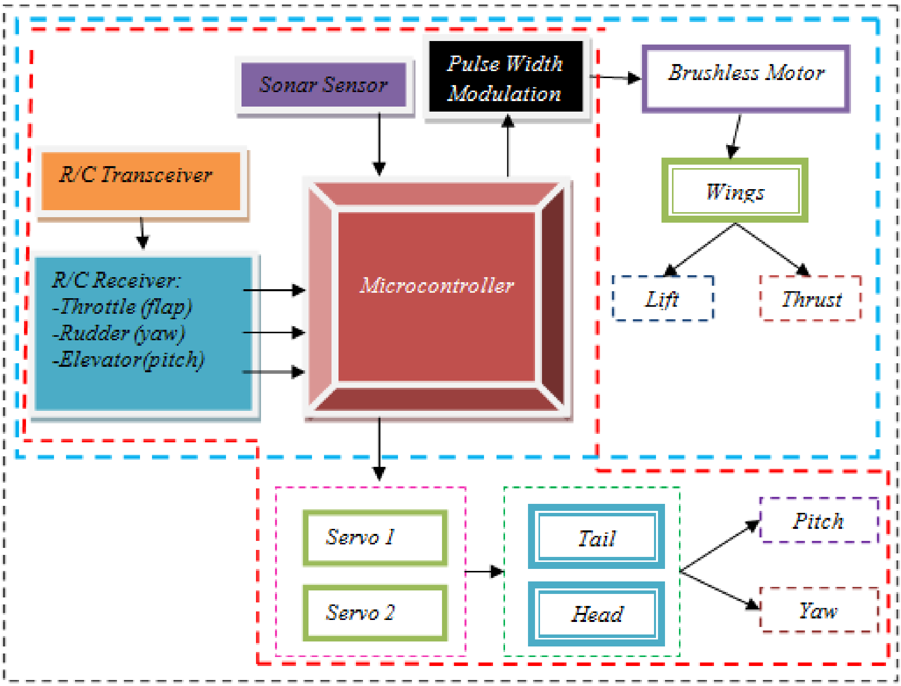


Figure 1. Block diagram of the system

Mechanical Design

The dimensions of the robot are considered based on the robot's load, while the determination of wing dimensions based on motor power and total weight of the robot. The dimension of the ornithopter wing is shown in Figure. 2. The ornithopter frame consists of carbon rods (2 mm, 3 mm and 5 mm in diameter), plywood (3.5 mm thick) and acrylic (2 mm and 5 mm thick). The ornithopter frame uses 3 mm diameter carbon rods and plywood. The inner wing frame uses 3 mm diameter carbon rods while the outer wing uses 2 mm diameter carbon rods. The wing membrane uses plastic.

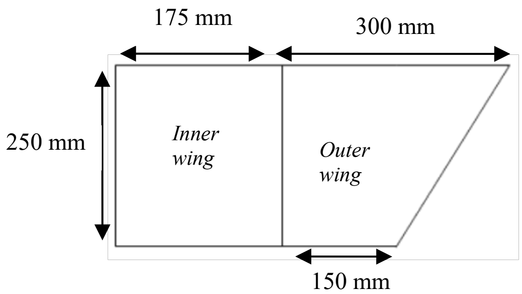


Figure 2. The dimensions of the ornithopter wing

The wing design includes the articulation design, which includes hinges, wing arm adapters and limiters. The hinge was made of 2 mm thick acrylic material, the adapter was made of 6 mm diameter stainless pipe, and the limiter was made of 2 mm thick acrylic. Figure. 3 shows the wing articulation mechanics, while Figure. 4 shows the wing mechanics.

(a) (b) (c)

Figure 3. (a) Hinge; (b) Limiter; (c) Adapter

Figure 4. Wing mechanics

Based on the wing dimensions, the force on each wing can be calculated. Due to the robot wing has no airfoil (flat plate), the determination of lift force (F_L), drag force (F_D), and thrust force (F_T) values can be calculated using Eq. 1-3.

$$F_L = \frac{1}{2}\rho v^2 s C_L \quad (1)$$

$$F_D = \frac{1}{2}\rho v^2 s C_D \quad (2)$$

$$F_T = L \sin\alpha - D \cos\alpha \quad (3)$$

with ρ is air density (kg/m^3), v is velocity (m/s), s is wing planform area (m^2), C_L is lift coefficient, C_D is drag coefficient, L is lift resultant, D is drag resultant, and α is angle of attack. C_L and C_D depend on various factors, including the geometric shape of the object, angle of attack, surface properties, and type of fluid flow.
Here are the wing specifications:
- s = 0.1 m^2 (see Figure. 2)
- v is assumed as in Table 1
- α = 15º = 0.261799388 rad (angle of attack assumption)
- Robot load = 1.8 N

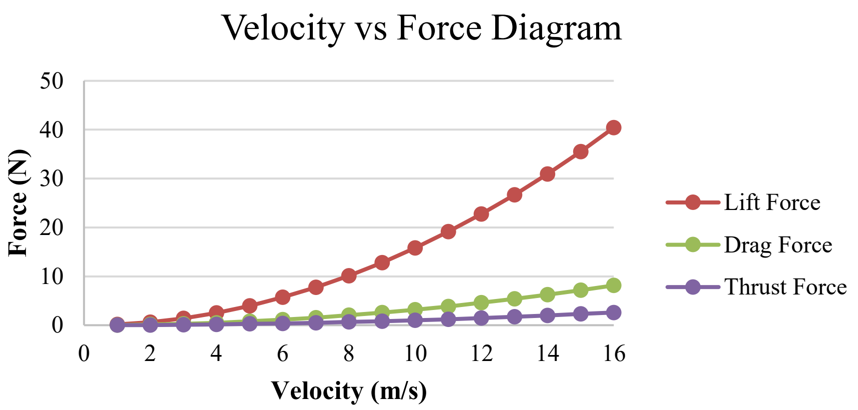
RESULT AND DISCUSSION

Based on the previous section's wing specification data, the forces' calculation results can be obtained as shown in Table 1 below.

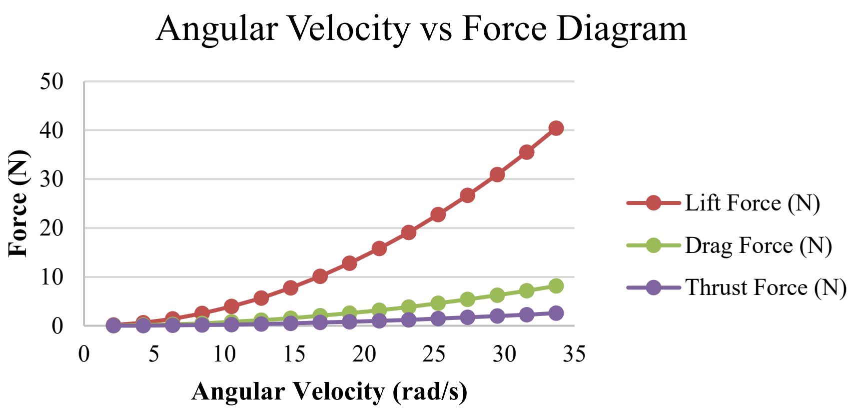
Table 1. Calculation of all forces on wings with flat plate airfoil

v (m/s)	ω = v r (rad/s)	F_L (N)	F_D (N)	F_T (N)	C_L/C_D
1	2.10526	0.15791	0.0318	0.01015	4.96572327
2	4.21053	0.63165	0.12721	0.0406	4.96541152
3	6.31579	1.42122	0.28623	0.09136	4.96530762
4	8.42105	2.52662	0.50886	0.16242	4.96525567
5	10.5263	3.94784	0.79509	0.25378	4.96527437
6	12.6316	5.68489	1.14493	0.36544	4.96527298
7	14.7368	7.73776	1.55838	0.4974	4.96525879
8	16.8421	10.1065	2.03544	0.64967	4.96526549
9	18.9474	12.791	2.5761	0.82223	4.96525756
10	21.0526	15.7914	3.18037	1.0151	4.96527133
11	23.1579	19.1075	3.84825	1.22827	4.96524394
12	25.2632	22.7395	4.57973	1.46175	4.96524904
13	27.3684	26.6874	5.37482	1.71552	4.96526395
14	29.4737	30.9511	6.23352	1.9896	4.96526842
15	31.5789	35.5305	7.15583	2.28398	4.96525210
16	33.6842	40.4259	8.14174	2.59866	4.96526541

After the data is obtained, the data is then plotted on a graph to see the trend. Figure. 5 shows the velocity vs force, angular velocity vs force diagrams, and velocity vs C_L/C_D. The diagrams show that lift force increases significantly as velocity and angular velocity increase. The drag force also increases as velocity and angular velocity increase. Furthermore, the thrust only increases slightly as the velocity and angular velocity increase. At the same velocity and angular velocity point, lift force is higher than drag force. It means that the value of C_L/C_D is high (higher than 1). Figure. 5(c) shows the trend of slightly decreasing the C_L/C_D as the velocity increased. The trend is also the same for angular velocity vs C_L/C_D. In addition, from the diagrams, it can be concluded that the ornithopter design should be improved to get the thrust force higher than drag force, so that the ornithopter may fly.



(a)



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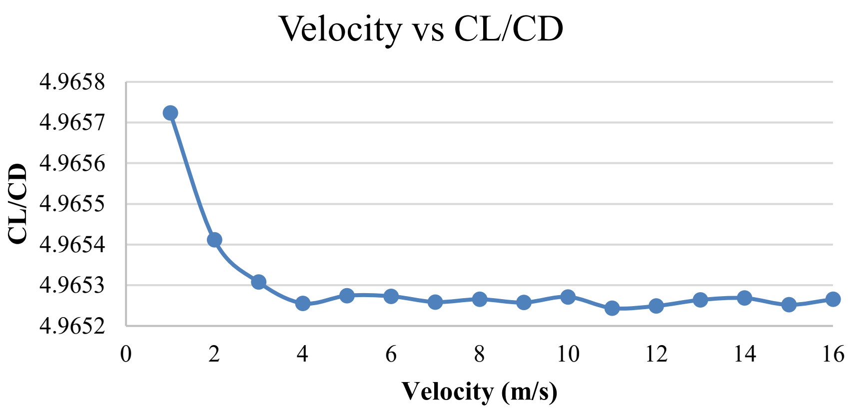

(c)

Figure 5. (a) Velocity vs force diagram and (b) angular velocity vs force diagram (c) velocity vs C_L/C_D

The next step was mechanical assessment of the wing's mechanical which involves measuring the velocity of the brushless motor under conditions where the wing was both installed and not installed while adjusting the throttle settings. The test used a tachometer to measure brushless velocity. Table 2 presents the results of the velocity assessment conducted on the brushless motor where the robot's wings were not installed. The table shows that the velocity increases stably at throttle 33.3%. Conversely, Table 3 presents the outcomes of the velocity analysis performed on the brushless motor where the robot's wings were installed. The velocity values in Table 3 are smaller than those in Table 2 as the brushless had to carry the wing load to move the wing and was also affected by the gear ratio.

Table 2. Value of brushless motor velocity with no-load

Throttle (%)	No-load brushless motor velocity (rpm)
16.6	12000
33.3	22000
50	25600
66.6	27000
83.3	28500

Table 3. Value of brushless motor velocity with load

Throttle (%)	Brushless motor velocity with load (rpm)
16.6	6000
25	6200
33.3	6400
41.6	6800
50	7000

Lift force testing was conducted by hooking the robot to a spring balance. During the testing phase, the robot was suspended using two spring balances positioned both above and below the robot, as shown in Figure. 5. In the testing process, 5 samples were taken with a maximum throttle value of 50%. The spring balance needle was observed to move upwards when the wings flapped, indicating the robot's capability to lift its body weight. Conversely, a downward force was evident on the spring balance needle, demonstrating the effects of both the robot's weight and the wing flapping. Table 4 shows the results of the lift force test.

Figure 5. Lift testing

Table 4. Robot weight change on spring balance against wings' velocity

Throttle (%)	rpm	Flapping frequency (Hz)	Lift force (N)	Down force (N)	Total lift (N)
16.6	6000	0.83	0.4	0.3	0.1
25	6200	0.86	0.45	0.3	0.15
33	6400	0.88	0.55	0.35	0.2
41.6	6800	0.94	0.55	0.4	0.15
50	7000	0.97	0.6	0.4	0.2

Based on the test results data, it was found that the lift force was greater than the down force, so that, theoretically the robot could fly. However, the total force generated by the robot was quite small, as the ability to fly needs to be improved. The largest lift occurred when the frequency values were 0.88 and 0.97.

CONCLUSION

After conducting this research, it can be concluded that

1. For the single wing, at the same velocity and angular velocity point, lift force is higher than drag force. It means that the value of C_L/C_D is high. However, the ornithopter design should be improved to get the thrust force higher than drag force, so that the ornithopter may fly. In addition, the velocity started to increase stably at throttle 33.3%.
2. For the ornithopter, it was found that the lift force was greater than the down force, so that, theoretically the robot could fly. However, the total force generated by the robot was quite small, as the ability to fly needs to be improved. The largest lift occurred at the frequency values of 0.88 and 0.97.

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