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QUADCOPTER BODY FRAME MODEL AND ANALYSIS

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***Abstract*—**Quadcopter frame modeling is useful to analyze the reliability of body frame part and to help determine the type of rotor and propeller in order to assure the necessary flight acceleration. Quadcopter flight stability is influenced by the resulting thrust, by the distance between each rotor propeller and also by the frame rigidity; the frame has been designed to be as light as possible, meanwhile maintaining the strength to carry the load. Solidworks software has been used to design and analyze using Finite Element Analysis (FEA) method the quadcopter frame - having folded size of 560 (mm) square - also a 406x127 (mm) propeller and rotor's angular velocity and air flow produced around the propeller. The FEA method showed that the presence of rotational velocities in each propeller flow field will significantly affect the thrust efficiency which can cause flight instability or body frame vibration.

***Keywords*—**Quadcopter; frame; CAD; Solidworks; airflow.

I. INTRODUCTION

THE quadcopter design concept is based on existing literature. There are several qualities to be fulfilled while designing the quadcopter body frame, such as creating a good rigid body as light as possible and capable to carry weight, also the placement of electronic components, sensors and rotors. Quadcopter's size depends on its usage. A 3D model of quadcopter was designed using Solidworks and Finite Element Analysis (FEA) to ascertain the stress and weight of quadcopter body frame. In its implementation, quadcopter will be made using 3D printing machine, thus every detail of body frame is very important. Computer-Aided Design (CAD) is used to assist in the creation, modification, analysis, or optimization of the design.

Quadcopter frame size was established firstly, so the type of rotor and propeller which will be used can be selected accordingly. The chosen square frame size was 560 (mm) which was considered the right size to carry the load. The magnitude of rotor's speed rotation and the type of propeller used will affect the thrust. Thrust is the force exerted by a propeller which moves a quadcopter through the air. Knowing the magnitude of thrust produced by each rotor, the body frame strength and rigidity can be analyzed using Solidworks software.

Propeller with size 406x127 (mm) was analyzed to study the effect of its airflow towards body frame. Models for wind disturbances estimation are used to improve positioning accuracy by both eliminating the effect of the wind on the feedback position control law or the effect of the expected wind disturbance [1].

II. QUADCOPTER BODY FRAME MODELING

In designing quadcopter's body frame, one must regard the total weight which will be borne by quadcopter such as the weight of electronic, frame, landing gear, rotor and sensor [2]. For this model, the size was determined firstly so that the type of rotor and propeller used can be calculated in terms of quadcopter ability to carry weight. As seen in Fig. 1., the dimension of quadcopter is 560 (mm) (length) x 560 (mm) (width). All the dimensions in the figure below are in millimeters. To obtain the lightest weight possible yet with decent rigidity so as to make it possible to carry weight and fly stable, a perforation was made into the body frame while keeping in mind the symmetry and the centroid of the frame.

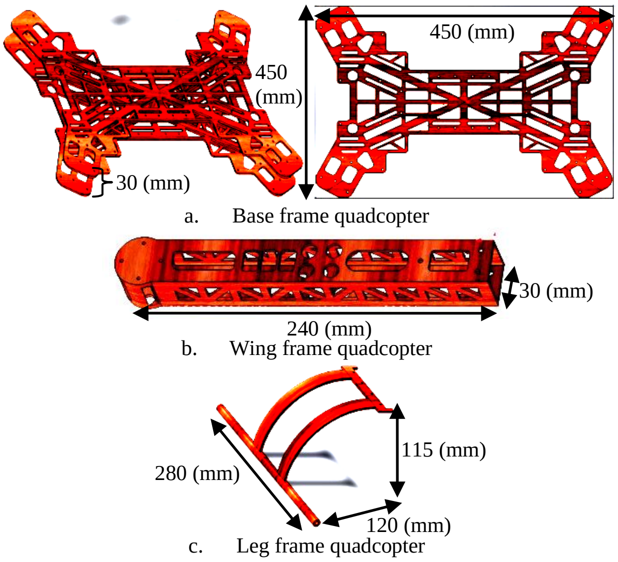
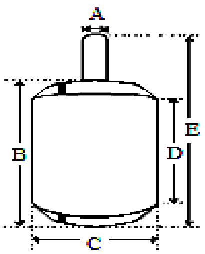


Fig. 1. The 3D CAD model for quadcopter

The body frame was divided into three parts: a base frame, sing frame and leg frame. The base frame was designed using two pieces of the same size for the upper base frame and bottom base frame. The distance between wheelbase is 30 (mm) and placed diagonally for several purposes: to connect the upper and bottom part, to gain body rigidity and also to put the electronic system. The double wheelbase was also designed to make a better join between wing frame and base. To lessen the impact when landing, the landing frame/bottom part uses plastic circular model and foam can also be added. This is a minor part of the quadcopter thus is not analyzed in this model. These designs minimalize the use of bolts and screws especially in the mainframe, whereas the center of mass to place components and the sensor is in the middle. Aside to lessen the quadcopter weight, this design also meant to anticipate the loose of screw and bolts caused by vibration when the quadcopter is flying.

Quadcopter's frame can be made from various materials. Several materials such as plastic, carbon fiber, aluminum and wood were used in previous existing research so the static structural analysis result can be analyzed and compared [3]. Prior to analyzing the strength and rigidity of body frame, the type of rotor and propeller which will be used must be decided first. This research uses rotors having data presented in TABLE I.

TABLE I
ROTOR SPECIFICATIONS

Rotor Specifications	Value	Rotor Sketch
Kv (rpm/v)	640	
Weight (g)	97	
Max Current (A)	30	
Resistance (mh)	120	
Max Voltage (V)	19	
Power (W)	550	
Shaft A (mm)	4	
Length B (mm)	26	
Length C (mm)	42	
Can length (mm)	11	
Total length (mm)	31	

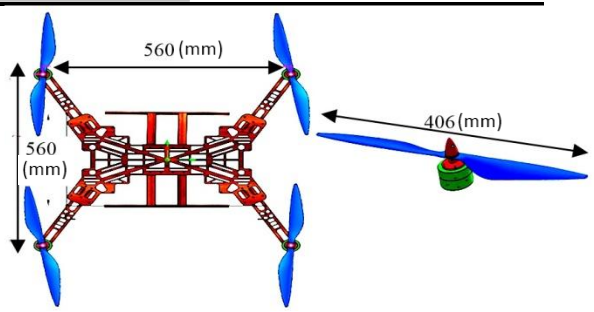


Fig. 2. Body frame quadcopter model

The rotor is connected with the 406x127 (mm) propeller. Fig. 2. shows the CAD and the connection between frame, rotor and propeller. With this design, it is possible to conduct the FEA on body frame quadcopter.

III. QUADCOPTER RIGIDITY ANALYSIS

Analysis of the quadcopter body frame rigidity was studied considering the equality between the vertical thrust produced by each rotor and quadcopter mass during flight. As mentioned before, the thrust generated by each rotor depends on the type of rotor and propeller used. In propeller's rotation process, the changes in velocity and direction of the airflow around propeller are associated with force alteration based on the volume of air involved, also known as an aerodynamic movement. Equation (1) is Newton's Law of Motion which can be used to calculate the resulting thrust.

Newton's Law of Motion shows that the force (F) acting on an object is equal to its mass (m) times its acceleration (a) or equivalently to its momentum change rate. Basically whenever there is a change of momentum, there must be a force causing it. In this case, since momentum is a vector quantity, the change in direction of the airflow around the propeller must be related to force on the volume of air involved.

$$\mathbf{F} = \frac{\mathbf{d(mv)}}{\mathbf{dt}} = \mathbf{m.a} \tag{1}$$

This theory can be used to explain relationships between thrust, induced velocity and power in the rotor and propeller. On the mechanical principles of the action of propellers, the thrust (T) was connected to momentum change of the flow which is affected by the propeller. Based on fluid dynamic theory, the mass rate of flow (in this case airflow around propeller) in hovering/steady movement condition can be calculated based on surface area (A) with air pressure. Equation (2) shows that the air pressure force depends on the air density (ρ) and velocity of air (v_i) [4]. According to momentum conservation, the thrust on the disc is equal to the overall rate of increase of axial momentum of the air.

$$\mathbf{T} = (\rho A v_i).v_0 \tag{2}$$

The propeller effects a pressure change which draws the air in front of it and then pushes it out (accelerated by the propeller), represented by V_0. This means that the air velocity accelerated by the propeller is approximately twice of a maximum of the air velocity ($v_0 = 2 v_i$; $v_i = ½ v_0$). The velocity delivered to the air above and below the propeller surface area [5]-[6].

$$\mathbf{T} = \frac{\pi}{8} D^2 \rho v_0^2 \tag{3}$$

The air velocity accelerated by the propeller (m/s) depends on the magnitude of rotor's angular velocity (revolutions per second) and the space in which the propeller will travel onward through a solid medium with one complete revolution (propeller pitch). Equation (3) is used to calculate the estimated thrust produced by a single rotor depending on the angular speed of the rotor. The amount of thrust generated by a 406x127 (mm) propeller can be seen in Fig. 3.

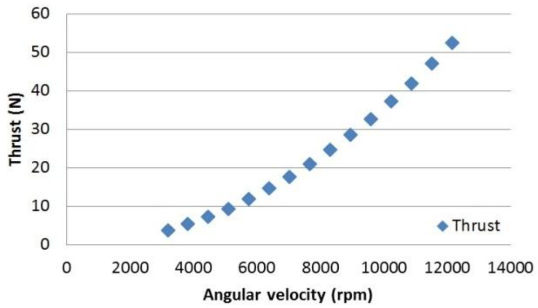


Fig. 3. Thrust for propeller 406x127 (mm)

Related to quadcopter body frame, the amount of resulting thrust can be used to calculate the rigidity of the designed frame. The maximum resulting thrust was 52 (N) or equivalent with 5302 (gram-force) for one rotor in a quadcopter.

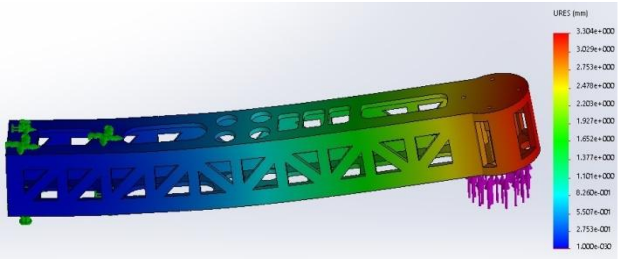


Fig. 4. Wing frame displacement analysis

Fig. 4. shows the maximum displacement which occurred on the rotor (3.3 (mm)) and on the center of wing frame (between 0.8 and 1.7 (mm)). The material used is plastic with an elastic modulus of 3000 (N/mm^2). This means the quadcopter has a good rigidity with designed wing frame size. The total weight of the overall frame is 560 (gram).

IV. Quadcopter Body Frame Analysis Related to Propeller

In body frame design, the distances between rotors determine the propeller's size. The propeller's size and its angular velocity will determine the magnitude of airflow and thrust produced. Airflow variations cause unexpected aerodynamic forces through changes in thrust conditions and un-modeled blade-flapping dynamics [7]. The opposite pair of the propeller will rotate in the same direction, as shown in Fig. 3. There is a limitation on the maximum size of the propeller that can be used based on the maximum torque of rotor and the magnitude of airflow produced by each rotor. To attain quadcopter flight stability with respect to space area, it is better to design the body frame and have control surface which, together with the aerodynamic, shapes of the rest of the airframe. The result is in the form of stability characteristics. This can be done by minimizing the disturbance from air turbulence and also from natural occurrences. Quadcopter was designed to have aerodynamic surfaces which are used to keep a steady flight path through air mass. The air mass moves relative to spatial coordinates then the quadcopter will move with the air mass. Therefore the aircraft can be very responsive to the air turbulence [8].

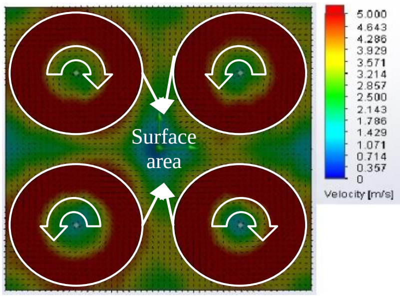


Fig. 5. Isosurface airflow around propeller

The torque generated can be measured based on the specification of the rotor used, which amount is 640 (rpm/v) and max voltage used is 19 (V). This means the rotor's maximum velocity is 12160 (rpm). If there are four rotors with similar maximum velocity and with a propeller diameter of 406x127 (mm), then the maximum wind velocity is 5 (m/s) on each propeller. The biggest wind velocity is in the chord line/coefficient thrust of the propeller. Besides that, airflow is also produced on the outside surface area of propeller rotation, which is between 2.5 and 4 (m/s). It is important to consider the maximum restriction propeller size so they will not disrupt each other. Fig. 4. shows the isosurface airflow occurred between two propellers.

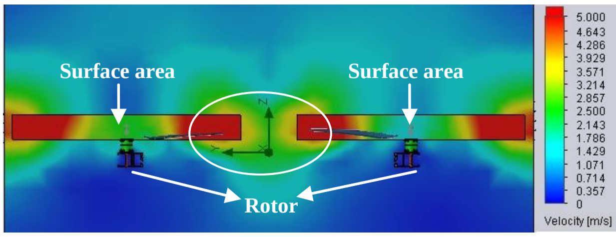


Fig. 6. Isosurface airflow between propellers with 12160 (rpm)

By maximizing the propeller's speed rotation, the airflow velocity occurred between two propellers is between 2 and 3.5 (m/s). In this condition, rotation air in propeller is still affecting each other. If the voltage used on the rotor is 12 (V), then the rotation movement generated is 7680 (rpm) and the airflow around propeller can be seen in Fig. 5.

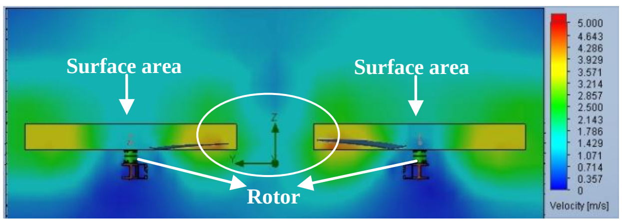


Fig. 7. Isosurface airflow between propellers with 7680 (rpm)

To better preview the propeller's airflow, a computation was done using Solidworks flow simulation for rotor's angular velocity of 12160 (rpm) and 7680 (rpm) as can be seen in Fig. 6. At the inlet airflow around propeller it is specified the air absolute velocity magnitude and also its components; in this case the velocity is parallel to the horizontal axis, therefore it does not have any component in the ordinates [9]. The air velocity occurred between two propellers is marked by a yellow circle. With maximum angular velocity, about 50% of maximum air velocity produced occurred between these two propellers. This great amount of air velocity was caused by an oversize propeller or exorbitant angular velocity. Numerical results show that the presence of swirling velocities in the flow field significantly affects the thrust vectoring efficiency of the rotor and computational fluid dynamics calculations were carried out using Reynolds-averaged Navier–Stokes equations [10]. This condition will also inflict the instability of thrust produced by each rotor, because the air velocity was affected by outlet airflow generated by surrounding rotor. Compared with an angular velocity of 7680 (rpm), the air velocity produced was smaller than 20% of its maximum, thus it can be said that air velocity produced by every propeller movement are not affecting each other.

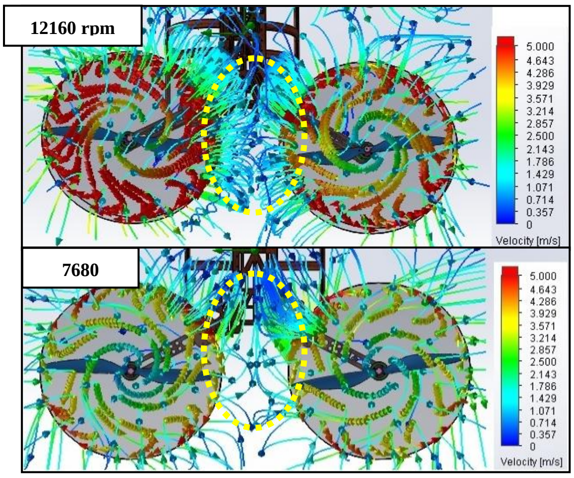


Fig. 8. Flow simulation around propeller

To reduce the disturbance by the propeller, one can choose smaller propeller size or reduce the voltage on rotor thus decrease the generated thrust. The voltage supply of 12 (V) and 7680 (rpm) will generate a thrust of 21 (N) with wind velocity around propeller of 1 (m/s). Other things that affect the airflow motion are variable pitch and thrust from propeller which can also be analyzed using computational method [11].

V. CONCLUSION

The quadcopter body frame which was designed with Solidworks software has a good rigidity and the size also compatible with the specification of rotor propeller used. The rigidity of plastic-based frame with a weight of 560 (gram) has a maximum displacement of 3.3 (mm) for 52 (N) thrust on the wing frame part. With the rotor specification stated in this research, 560 (mm) distance between rotor and 406x127 (mm) propeller, the maximum angular velocity that can be used is 7680 (rpm) which generated 21 (N) thrust. This is because the airflow produced between two propellers must not interplay, thus generate a stable thrust and not causing vibration on the body frame. For the initial analysis, the generated thrust can be calculated using momentum and fluid dynamic theory. However to get a better result, an experimental method is preferable.

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