Design and development of heavy-lift hexacopter for heavy payload

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***Abstract*— Research on multicopter nowadays is rapidly growing in many fields of application. One of the problems in the multicopter application is the ability to lift a heavy load that requires the careful design and selection of the proper type of multicopter for its ability in carrying out the missions involving the heavy load lifting. One type of multicopters that is often used is hexacopter. This paper describes the design of hexacopter that lift a heavy load. The design is done by calculating and analyzing the constraints and the criteria by the aid of software. The first flight experiment proved the capability of the designed heavy-lift hexacopter to fly in stable attitude while carrying a heavy load.**

***Keywords*— design; heavy-lift hexacopter; payload; thrust;**

I. INTRODUCTION

Unmanned Aerial Vehicle (UAV) becomes popular in the world of science because of its various applications in this life such as search and rescue, monitoring, firefighting, surveillance, agriculture, aerial photography and others[1, 2]. Based on its lifting mechanism, the UAV is divided into rotor wing and fixed wing. The multirotor included in the wing rotor group is categorized by the number of propulsion motors such as helicopter, tricopter, quadcopter, hexacopter, and octocopter. Many researchers conducted research in this area such as autonomous helicopter control[1], tricopter modeling[3, 4], attitude and altitude quadcopter movement control[5, 6], modeling and controlling hexacopter[7, 8], octocopter navigation control[9]. The control types that are used in this multirotor study i.e PID controllers[10], PID + LQR[11], sliding mode controllers[12], feedback linearization[8], backstepping[13], and Neural Network[14]. Advantages of the multirotor were included the ability of vertical takeoff and landing (VTOL) does not require a runway to fly, hovering ability and maneuver to perform the mission. The differences in the multirotor type related to the difference in the ability in lifting the load due to the addition of motor, while poses a new problem that causes the system to become more nonlinear and difficult to control. Since the mission is lifting a heavier load, thus the main choice of the multirotor type is hexacopter or octocopter. Although the octocopter has the ability as a hexacopter, it cost more price due to the more number of the motors. Therefore, hexacopter is selected to be designed as heavy lift carrier as it discussed further in this paper.

The previous work, heavy-lift hexacopter control has been used neural network[14, 15] but it discussed about movements of hexacopter and control system that used in hexacopter. While in this paper the focus of discussion on heavy-lift hexacopter design that will be used for autonomous control. It is difficult to design a big hexacopter and the ability to lift heavy weight. In this paper, the purpose is the ability to fly and lift more loads so that design becomes crucial for the development of hexacopter. Hexacopter with heavy payload has also been researched in[16] but it still in the design stage and has not flown yet while the power delivered by the tethered cables that limit its flight altitude. The other researcher discussed design and construction hexacopter for high endurance[17] but this hexacopter configuration combines two large propellers with the propeller on the quadcopter. So, the control uses the quadcopter system but the resulting thrust is the same as the hexacopter. Thus, the analysis and design are different from the hexacopter that uses six rotors as the driver. In designing the hexacopter, it is necessary to consider the following factors: a total weight that can be lifted, the thrust, motor type, propeller type and size, the material composition of the frame, and flight time. Due to these factors, it is expected that the design could achieve the objectives and overcome flight performance problems and the change of the load distribution due to the additional load[18]. The next step is to customize the design by supporting components such as Electronic Speed Controller (ESC), Brushless DC motor, battery, flight controller, GPS and compass and remote controller.

II. DESIGN OF HEAVY-LIFT HEXACOPTER

A. *Hexacopter configuration*

Hexacopter uses six motors that will rotate six propellers. This hexacopter lifting movement utilizes the thrust that is generated by the propeller combination of hexacopter frame. The frame configuration is generally recognized as two type: the Plus (+) and X configurations as in Fig. 1. The Hexacopter has 6 degrees of freedom (DOF), where the six degrees of freedom are affected by the rotational speed of each rotor, thus both frames will have different motion dynamics models. In this research, the Plus (+) configuration frame is used.

Fig.1 shows that each arm is connected to a brushless DC motor and has a propeller (fixed-pitch) so the rotor can force the air flow downward to generate the lift force. The direction of rotor rotation has two directions, i.e. three counterclockwise rotors (Counter Clock Wise; CCW) and three other rotors clockwise (Clock Wise; CW). So, it is clearly seen that the dynamic motion of hexacopter is simply influenced only by the speed of motor rotation.

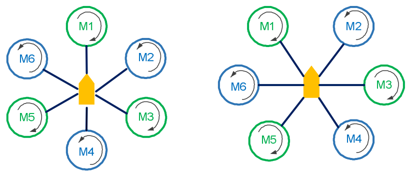

Fig. 1. Frame configuration

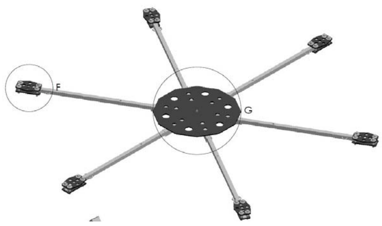

Fig. 2. Heavy-lift hexacopter frame design

The frame should be constructed from the lightweight material but strong enough to support its operational weight and structural load. Hence, it is necessary to analyze the flexibility and strength of the composing material of the frame. The design of this frame is hexagram with six equal long arms that attached to the center of a doubled hexagonal plate of as shown in Fig. 2.

B. Thrust and Motors

As the propulsion element for the hexacopter, the motor is the most important component. However, before determining the capacity of the motor applied in the design, it is necessary to know the total weight that will be lifted and the thrust which is required to lift the heavy load of hexacopter. The calculation to determine the thrust per motor as in the following equation:

$$Thrust = \frac{total\ weight\ x\ 2}{number\ of\ \ motor} \tag{1}$$

Moreover, static thrust can be calculated by the following equation[19]:

$$T^3 = \frac{\pi}{2} D^2 \rho P^2 \tag{2}$$

In this equation, T is thrust, D is the diameter of the propeller, ρ is the air density, and P is the motor power. This calculation will be combined with the following calculations were[19]:

$$Power = Kp\ x\ D^4\ x\ Pitch\ x\ (\omega)^3 \tag{3}$$

Where Kp is the propeller constant, D is the diameter and RPM is the motor rotational speed. The value of this RPM is calculated from the KV constant and the voltage that is used by the motor. As the main driving force in the Hexacopter system is used BLDC motor that has an advantage, where its structure does not use brush and commutator so that this type of motor will be more efficient than usual DC motor. BLDC motor can produce high RPM (Revolutions per minute). The main parameter of concern of BLDC motor is KV (rpm/volt), where this KV is a parameter that states the magnitude of rpm increase for each unit of voltage that is used.

C. Propeller Performance

The distance streamed by the fluid due to one rotation of propeller's blade is defined as the pitch parameter that is often noticed in the selection of propellers. Thus, if the pitch and diameter of the propeller are larger, so the motor rotation will be slower and the lifting force that is produced is large. So, if the hexacopter can lift the heavy load, it required large diameter propellers and large pitch. The thrust style equation of this propeller is [18]:

$$F_{TH} = \rho C_t n^2 D^4 \tag{4}$$

Where ρ is the air density, n is the rotational speed of the propeller, Ct is the thrust propeller coefficient, and D in meters is the diameter of the propeller. For each speed, this Ct value varies with a small value so it can be ignored. While the power that is generated from the propeller can be calculated [18]:

$$P_p = \rho C_p n^3 D^5 \tag{5}$$

Cp is the power coefficient of the propeller that is obtained from the rotation. This Cp value changes with speed. For the torque on the propeller is generated based on the following equation:

$$T_q = \frac{P_p}{\omega} \tag{6}$$

Where ω is the propeller's angular speed.

D. Capacity of battery

Batteries are the power source to run all the components on the hexacopter. The battery also affects the flight time so that proper calculations are required to produce optimal results. Therefore, to get the proper power and load combinations, the batteries that are used must have more current than motor currents. The parameter to be considered in the selection of the battery is the number of cells, discharge, and capacity. The number of cells determines the voltage of the battery in an empty state. Then the discharge shows how much current rating / current velocity can be released, and the capacity shows how long the battery can work on certain amperes.

III. EXPERIMENT RESULT

The heavy-lift Hexacopter frame consist of stainless steel material for its strength and lightweight characteristics. Furthermore, a loading simulation of this frame will be done by analyzing the static and dynamic materials. The force that is given as the load on this simulation is 100 N.

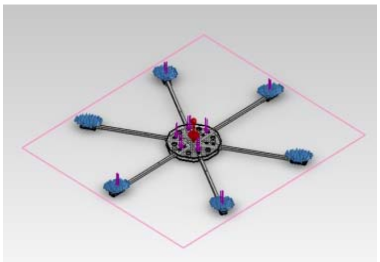

Fig. 3. Heavy-lift hexacopter stainless steel frame design

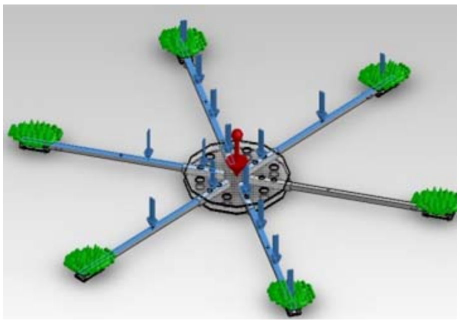

Fig. 4. Placement of styles on the frame

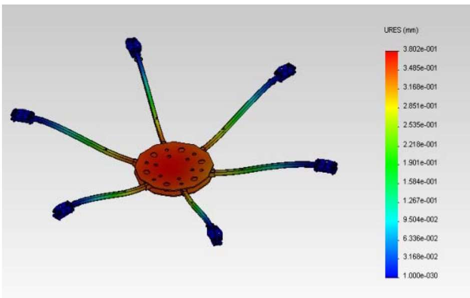

Fig. 5. The displacement analysis on the frame

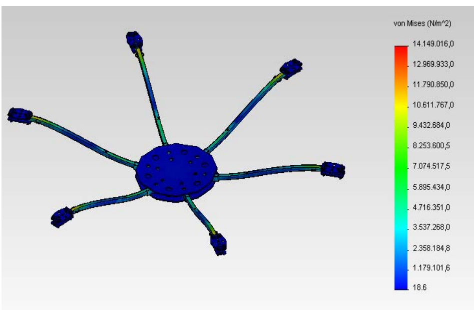

Fig. 6. Stress analysis on frames

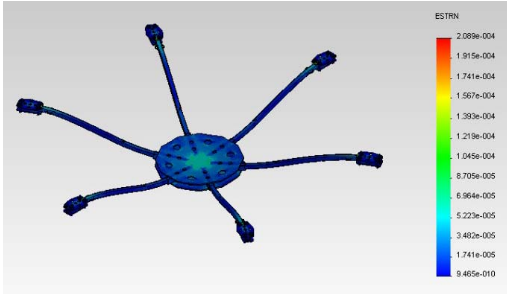

Fig. 7. Strain analysis on the frame

The Frame of heavy-lift hexacopter is made of stainless steel as designed in Fig. 4. The maximum displacement value is 0.302 mm and smaller than the overall arm length suitable to Fig. 5. Then Maximum von misses pressure is 14.149 MPa as shows in Fig. 6 on the arm attached to the hexagonal plate that is compared to the material is used. Thus, the structure is concluded as safe for flight. After all, in Fig. 7, the maximum strain is also occurred at 0.2. This proves that stainless steel as frame material can be used safely after being tested with 100 N of force. It can be seen on the color in the picture on a frame that doesn't go to red level according to parameter analysis from the picture. In this frame will be placed all the components either on the center plate to the arm.

Fig. 8. Frame and component

While the weight of each component is as follows:

TABLE I. COMPONENTS WEIGHT

No	Item	Unit	Berat (gr)
1	Battery	4	6016
2	Motor	6	5064
3	ESC	6	612
4	Propellers	6	4800
5	Body	1	3500
6	*Ardupilot*	1	34
7	GPS	1	20.6
8	Regulator	1	25.3
9	Radio Receiver	1	19.4
	TOTAL		**20091.3**

With a total weight of 20,091.3 grams is known then the thrust of each motor is determined as follows

$$Thrust = \frac{total\ weight\ x\ 2}{number\ of\ \ motor}$$

$$Thrust = \frac{20.091{,}3\,x\,2}{6} = 6.697{,}1\ gram$$

Thus, for the ability to fly and hover, the heavy-lift hexacopter must overcome the gravity force. Based on the above calculation, each motor must produce a thrust of 6,697.1 grams with the assumption that all motors have equal thrust. To ensure the thrust of the rotor that is used is capable of lifting and moving the hexacopter, it is necessary to measure the thrust of the rotor. Measurements are conducted in the rotation speed of BLDC motor and thrust force that is produced. BLDC motor speed measurement uses a digital tachometer where the output is already RPM. The thrust testing of this motor is as seen in the picture below

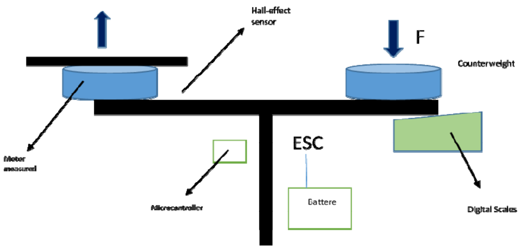

Fig. 9. Construction of rotor thrust measurement

From Fig. 9, the measurement is done by giving the variation of speed from minimal to maximal. The principle works by using the principle of a lever which at the end is placed the scales to measure the lift capability of the motor. Hall Effect sensors are used to measure speed. This measurement process is done by using a microcontroller. Each speed variation is also recorded speed and thrust style generated. From this measurement obtained the following results:

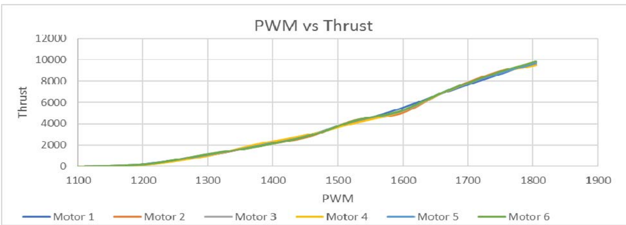

Fig. 10. Graph of thrust curve to angular velocity

The measurement results show that Hexacopter is able to fly because if it is seen from the average thrust force maximum of 9686,667 gr x 6 = 58120 gr will be able to lift Hexacopter which has a total weight of 20091 gr and if the payload that will be lifted is an amount of 20000 gr then the overall of total weight is 40091 gr. From the calculation, hexacopter is able to lift it and can fly.

Fig. 11. First flight of heavy-lift hexacopter

Fig. 12. The heavy-lift hexacopter hovering

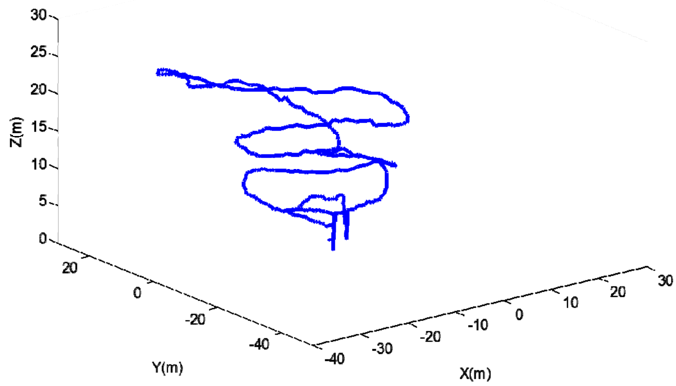

Fig. 13. Flight data of heavy-lift hexacopter maneuver movement

After completing the design, then the first flight scheduled in a flight test as photographed Fig. 11. The test is accomplished by performing several maneuvers illustrated in 3D graph trajectory Fig. 13. The trajectory shows that the heavy-lift hexacopter has been able to fly by maneuvering in the movement of the roll, pitch, and yaw and able to fly with a certain height that reaches 26 meters. This maneuver movement is formed circles with increasingly enlarged height as being shown in Fig. 13. The length of time this hexacopter heavy-lift flight reaches 15 minutes. The next test is flying with the payload. The payload is raised in the form of gallons of water weighing 15 kg. Heavy-lift hexacopter is still able to lift it as seen in Fig. 12. The flight time in this test reaches 11 minutes. The reduction of flight time due to the addition of weight from the payload and also the frame where put payload that causes the motor work to increase.

IV. Conclusions

This research has been able to design, analysis and constructs heavy-lift hexacopter that is capable of flying and lifting the payload. In testing the heavy-lift hexacopter is also capable of moving maneuver to a height of 26 meters and flight time is 15 minutes. Heavy-lift Hexacopter is also able to fly by lifting the payload. Future research that is done in the future is to control the heavy-lift hexacopter is autonomous.

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