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Simple Design of VTOL Hexacopter for Simple Navigation

Rafiuddin Syam, Abdullah Mappaita, Rahmat Hidayat, Amiruddin
Departement of Mechanical Engineering, Faculty of Engineering
University of Hasanuddin Makassar-Indonesia
Email: rafiuddin@unhas.ac.id

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***Abstract*-- The aims of this research are to determine how to create a simple hexacopter, the flying robot using six propellers. By using dynamic analysis it will be obtained the lifting force. To generate the lifting of each motor each UAV the doing simple maneuver of robot. Because each motor and propeller have the same type, it is enough to test one motor alone to determine the thrust and torque generated. Experiment of Hexacopter will then be done to fly through the path that has been made. Deviations will be measured to determine the amount of error generated. From the result of design, hexacopter successfully made from aluminum plate material and successfully tested fly.**
Keyword: *hexacopter*, UAV, kinematics, flying robot, VTOL.

I. INTRODUCTION

Unmanned aerial vehicles or unmanned aerial vehicle (UAV) has many benefits for human. For example the UAV can do searching victims of natural disasters, mapping, aerial photography, reconnaissance, and the delivery of goods. Hexacopter is one popular UAV because of the simple mechanism. Hexacopter also has the ability to land and take off vertically or vertical take-off landing (VTOL), do the hovering, and even fly indoors easily [1], [3].

Hexacopter has advantages compared to the conventional helicopters. The hexacopter that allows placement of the payload that is more and more easy to manage. Another reasn is the hexacopter has a minimum risk for falls due to the failure of the rotor [2].

II. MODELING OF *HEXACOPTER*

Hexacopter is multirotors which have six motors. All mounted on an arm that is connected symmetrically to the center. At one end of each arm mounted propeller powered by an electric motor. All propeller blades has a slope that is permanent, meaning the angle of the propeller blades cannot be changed. Unlike the classic helicopter which movement is controlled by changing the slope of the main propeller blades [3]. It makes hexacopter mechanically simpler than a traditional helicopter.

To know the position and orientation of hexacopter then we will use two frame coordinate axis, i.e. the axis of the immobile frame that stem from the earth and the framework that stem axis point of the center of gravity on the body hexacopter. Order immovable axis (earth frame) are denoted by E = {XE, yE, Ze} with Xe that leads to the north, yE which leads to the east and zB axis pointing up. Order axis of the body (body frame) are denoted by B = {xB, yB, zB xB} to lead to the next, the yB and zB leftward pointing up [1].

Figue 1. Reference Body of fixed frame.

The attitude of hexacopter is determined by the orientation of the axis of the body to the axis of the earth. Attitude is shown in rotation on the axis x, y, and z are comprised of roll, pitch, and yaw. Attitude is controlled by changing the motor rotation.

Yaw is rotation on the z-axis is denoted by R (ψ, z). This rotation seize the moment generated each propeller. For example if you want to play hexacopter clockwise with stable, then round three motor anticlockwise (motor 2, 4, and 6) accelerated and at the same time the rotation of the three motors is clockwise (motor 1, 3, and 5) slowed.

For matrix rotation respect to z-axis can be follow as below equation:

$$R(\psi,y) = \begin{bmatrix} c\psi & -s\psi & 0 \\ s\psi & c\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Pitch is rotation on the y-axis is denoted by R (θ, y). Pitch obtained by subtracting / adding the speed of the motor 1 and 6 as well as reduces / increases the speed of the motor 3 and 4 at the same time. This will cause the torque on the y axis.

As for the y-axis rotation matrix is shown in equation (2).

$$R\ (\theta,y) = \begin{bmatrix} c\theta & 0 & s\theta \\ 0 & 1 & 0 \\ -s\theta & 0 & c\theta \end{bmatrix} \tag{2}$$

Roll is rotation along the x-axis is denoted by R (ϕ, x). Roll obtained to reduce / increase the speed of the motor 1, 2, and 3 as well as reduce / increase the speed of the motor 6, 5 and 4 at the same time. This will produce a moment on the x axis.

The matrix rotation on the x-axis is shown in the equation below

$$R\ (\phi,x) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\phi & -s\phi \\ 0 & s\phi & c\phi \end{bmatrix} \tag{3}$$

The total Matrix R_B^E, transformation from the *body frame* to *earth frame*, can be obtained by multiply $R(\psi,z)$, $R(\theta,y)$ and $R(\phi,x)$, so that

$$R_B^E = R\ (\psi,z)\ .\ R\ (\theta,y)\ .\ R\ (\phi,x) \tag{4}$$

$$R_B^E = \begin{bmatrix} c\psi c\theta & s\theta s\phi c\psi - s\psi c\phi & s\theta c\psi c\phi + s\psi s\phi \\ s\psi c\theta & s\psi s\theta s\phi + c\psi c\phi & s\psi s\theta c\phi - c\psi s\phi \\ -s\theta & s\phi c\theta & c\theta c\phi \end{bmatrix} \tag{5}$$

Because R_B^E is matrix ortogonal, then transformation from the *earth frame* to *body frame* can be obtained with

$$(R_B^E)^{-1} = (R_B^E)^{T} = R_E^B \tag{6}$$

By using Newton-Euler formula for describe of dynamics equation can be follow as

$$\begin{bmatrix} mI_{3x3} & 0_{3x3} \\ 0_{3x3} & I \end{bmatrix} \begin{bmatrix} \dot{V}^B \\ \dot{\omega}^B \end{bmatrix} + \begin{bmatrix} \omega^B \times mV^B \\ \omega^B \times I\omega^B \end{bmatrix} = \begin{bmatrix} F^B \\ \tau^B \end{bmatrix} \tag{7.a}$$

wheren

m = mass (*kg*),
I = inertia of tensor (*Nms*^{2}),
V^B = $[u\ \ v\ \ w]^T$ is linear velocity of the *body* (*m/s*),
ω^B = $[p\ \ q\ \ r]^T$ is angular velocity of the *body* (*rad/s*),
F^B = Force of *hexacopter* pada *body frame* (*N*),
τ^B = moment of *hexacopter* on the *body frame* (*Nm*),
0_{3x3} = matrix 0 (null) with size 3x3,
I_{3x3} = matrix identity with size 3x3.

Because of cross vector can be obtained vector as in the multiply simteris matrix and the vector

$$a \times b = \begin{bmatrix} 0 & -a_3 & a_2 \\ a_3 & 0 & -a_1 \\ -a_2 & a_1 & 0 \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix} \tag{7.b}$$

And the inertia of tensor is diagonal matrix

$$I = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \tag{7.c}$$

On the equation (7.a) can be widely use as

$$\begin{cases} mI_{3x3}\dot{V}^B + \omega^B \times mV^B = \begin{bmatrix} m\dot{u} \\ m\dot{v} \\ m\dot{w} \end{bmatrix} + \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} \\ I\dot{\omega}^B + \omega^B \times I\omega^B = \begin{bmatrix} I_{xx}\dot{p} \\ I_{yy}\dot{q} \\ I_{zz}\dot{r} \end{bmatrix} + \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix} \begin{bmatrix} I_{xx} \\ I_{yy} \\ I_{zz} \end{bmatrix} \end{cases} \tag{7.d}$$

$$\begin{cases} \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix} = \begin{bmatrix} rv - qw \\ pw - ru \\ qu - pv \end{bmatrix} + \begin{bmatrix} \frac{1}{m}F_x^B \\ \frac{1}{m}F_y^B \\ \frac{1}{m}F_z^B \end{bmatrix} \\ \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} \frac{I_{yy} - I_{zz}}{I_{xx}}qr \\ \frac{I_{zz} - I_{xx}}{I_{yy}}pr \\ \frac{I_{xx} - I_{yy}}{I_{zz}}pq \end{bmatrix} + \begin{bmatrix} \frac{1}{I_{xx}}\tau_x^B \\ \frac{1}{I_{yy}}\tau_y^B \\ \frac{1}{I_{zz}}\tau_z^B \end{bmatrix} \end{cases} \tag{7.e}$$

Gravitation on the center of gravity of the hexacopter is on the direction of z axis. At the body frame, contributed of gravitation force F_G^B is

$$F_{grav}^B = R_E^B \begin{bmatrix} 0 \\ 0 \\ -mg \end{bmatrix} = \begin{bmatrix} mg\sin\theta \\ -mg\sin\phi\cos\theta \\ -mg\cos\phi\cos\theta \end{bmatrix} \tag{8}$$

If g is acceleration of gravity and driving force is the total lift force generated the entire propeller and always directed along the z-axis. On-the-fly, this style can be obtained by equation (9), b is a constant thrust (*Ns*^{2}).

$$F_{thrust}^B = b\sum_{i=1}^{6}\Omega_i^2 \tag{9}$$

There are obstacles (drag) that occurs at the time hexacopter fly. This drag will affect the acceleration in the x and y on the body frame. On-the-fly, this drag can be obtained by equation (10) with μ is constant (kg/s).

$$F_{drag}^B = \begin{bmatrix} -\mu u \\ -\mu v \\ 0 \end{bmatrix} \tag{10}$$

Air resistance is proportional to the square of the speed, size and shape of the object in accordance with equation (11). C is the coefficient of friction (dimensionless), Ai is the area affected by obstacles (m^2) and ρ is the density of air (kg / m^3).

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$$F_{air}^{B} = \begin{bmatrix} -\frac{1}{2}CA_x\rho u|u| \\ -\frac{1}{2}CA_y\rho v|v| \\ -\frac{1}{2}CA_z\rho w|w| \end{bmatrix} \quad (11)$$

The moment is is a force multiplied by the distance to the axis of rotation. At equations (12)-(14), Ω is velocity of *propeller* (*rad/s*), *l* is length of arm (*m*), *d* is drag factors (*Nms*^{2})

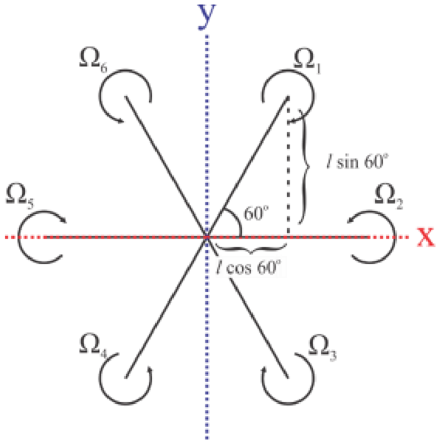

Figure 2. Geometrycal of *hexarotor*

By reducing Ω^1, Ω^2, Ω^3 and add Ω^4, Ω^5, Ω^6 a positive roll can be produced

$$\tau_{roll} = bl(-\Omega_2^2 + \Omega_5^2 + \frac{1}{2}(-\Omega_1^2 - \Omega_3^2 + \Omega_4^2 + \Omega_6^2)) \quad (12)$$

By reducing Ω1, Ω6¬ and add Ω3, Ω4 a positive pitch can be obtained.

$$\tau_{pitch} = bl\frac{\sqrt{3}}{2}(-\Omega_1^2 + \Omega_3^2 + \Omega_4^2 - \Omega_6^2) \quad (13)$$

By reducing Ω2, Ω4, Ω6 and add Ω1, Ω3, Ω5 we can get a positive yaw.

$$\tau_{yaw} = d(\Omega_1^2 - \Omega_2^2 + \Omega_3^2 - \Omega_4^2 + \Omega_5^2 - \Omega_6^2) \quad (14)$$

The rotation of the propeller effect of gyroscopes

$$\tau_{gyro} = \begin{bmatrix} -J_r\dot{\theta}\Omega_r \\ J_r\dot{\phi}\Omega_r \\ 0 \end{bmatrix} \quad (15)$$

By J_r is the rotational inertia of the propeller (*Nms*^{2}) and Ω_r = Ω_r-Ω_r + Ω_r-Ω_r + Ω_r-Ω_radalah overall speed propeller.

Differences acceleration rotation of the propeller generates a counter torque on the yaw inertia

$$\tau_{counter} = \begin{bmatrix} 0 \\ 0 \\ J_r\dot{\Omega}_r \end{bmatrix} \quad (16)$$

By combining the equations of motion, the final equation for the motion is hexacopter

$$\begin{cases} \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix} = \begin{bmatrix} rv - qw & +mg\sin\theta & -\frac{\mu}{m}u - \ldots \\ pw - ru & -mg\sin\phi\cos\theta & -\frac{\mu}{m}v - \ldots \\ qu - pv & -mg\cos\phi\cos\theta & +\frac{1}{m}F_{dorong} \ldots \end{bmatrix} \\ \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} \frac{I_{yy} - I_{zz}}{I_{xx}}qr + \frac{1}{I_{xx}}\tau_{roll} - \frac{1}{I_{xx}}J_r\dot{\theta}\Omega_r \\ \frac{I_{zz} - I_{xx}}{I_{yy}}pr + \frac{1}{I_{yy}}\tau_{pitch} - \frac{1}{I_{yy}}J_r\dot{\phi}\Omega_r \\ \frac{I_{xx} - I_{yy}}{I_{zz}}pq + \frac{1}{I_{zz}}\tau_{yaw} + \frac{1}{I_{zz}}J_r\dot{\Omega}_r \end{bmatrix} \end{cases} \quad (17.a)$$

$$\begin{cases} F_{dorong}^{B} = b\sum_{i=1}^{6}\Omega_i^2 \\ \tau_{roll} = bl(-\Omega_2^2 + \Omega_5^2 + \frac{1}{2}(-\Omega_1^2 - \Omega_3^2 + \Omega_4^2 + \Omega_6^2) \\ \tau_{pitch} = bl\frac{\sqrt{3}}{2}(-\Omega_1^2 + \Omega_3^2 + \Omega_4^2 - \Omega_6^2) \\ \tau_{yaw} = d(\Omega_1^2 - \Omega_2^2 + \Omega_3^2 - \Omega_4^2 + \Omega_5^2 - \Omega_6^2) \\ \Omega_r = \Omega_r - \Omega_r + \Omega_r - \Omega_r + \Omega_r - \Omega_r \end{cases} \quad (18.a)$$

III. Design of Hexacopter

Hexacopter created order consists of several parts, namely the middle, arms, and legs battery holder. Six arms connected symmetrically to the center. Holder battery is placed under the middle, separated by a spacer to make room for the cables of the ESC. The leg of hexacopter made higher in order to avoid the battery, the motor and propeller by other objects such as grass, water, dust, or other particles when taking off or landing.

The frame consists of a central part made of acrylic plate 5 mm, hexagonal shaped with a diameter of 190 mm. While the legs and arms are made of aluminum hollow along 240 mm, with a square cross-section 20x10 mm.

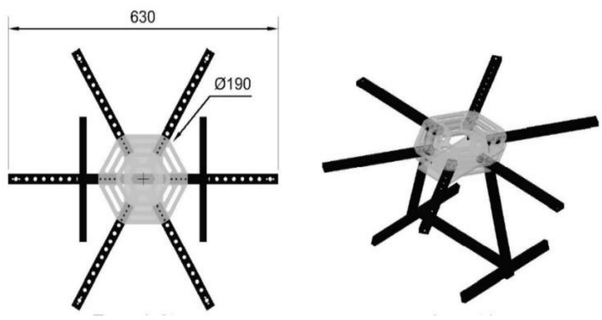

Figure 3. Design of Hexacopter frame

Because hexacopter using the motor and propeller of the same type. Then simply examine one bike only to find out the thrust force and torque is generated.

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The resulting thrust force on the propeller and the motor comes in line with the direction of the force adopted. To know the major thrust is generated, the motor will be placed on a digital scale. Propeller will be installed upside down such that the resulting thrust will push the motor down. To determine the motor torque generated when the rotating propeller. The motor will be mounted on an arm with a certain length. This arm will hit digital scales when the motor rotates.

. Hexacopter is flown to follow the path that has been made. Deviation made by hexacopter be measured as an error value.

IV. Basic Movement and Experimental Result

One way to control hexacopter is through the propeller. Each propeller generates thrust upward by pushing air downward. Because the source of the thrust is located outside the center of mass, differential changes in lift force can be used to play hexacopter. Round of the motor also produces a reaction torque in the opposite direction to the direction of rotation. Since most propellers rotate in one direction, the number of moments for all the motors have the same velocity is zero.

There are four basic movements: throttle, roll, pitch, and yaw. Controlling is done by changing the movement speed propeller. Hexacopter linear motion (fly along the surface) is controlled through the roll and pitch angles. To fly forward, hexacopter tilted forward. This will result in acceleration toward the front.

The major control of hexacopter is the throttle, it used to control movement in the vertical direction of the body. Because of the slope of the propeller fixed, then the direction of rotation of the thrust is fixed. The biggest task of the throttle is to defy gravity. When adding or reducing throttle, hexacopter will move upwards or downwards. If hexacopter is in a tilted state, the thrust will move hexacopter towards tilt.

The driving force in multirotor caused by the lifting force generated propeller. Because of the angle of attack (pitch) of the propeller is fixed, then to raise or lower the lift force is by raising or lowering the angular velocity of the propeller.

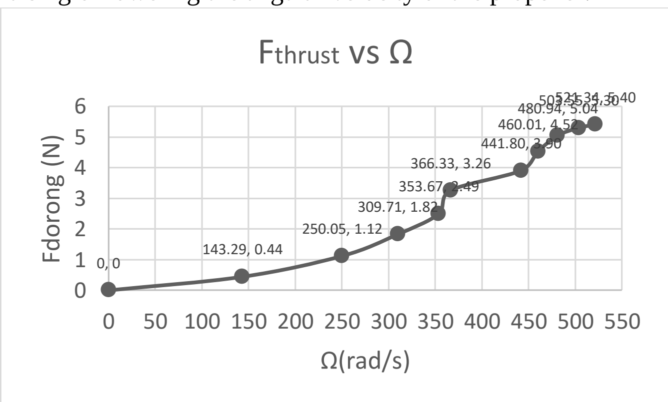

Figure 9. The relation between Thrust F_{thrust} (N) with Angular velocity Ω (rad/s).

Because of the propeller rotated dimensions and mass large enough, then to be able to provide high corner speeds, the motor requires power (watts) is quite large.

Because the measurements are made with tools that lack of precision, such as the tachometer is still using the system touch. The result in of accurate data retrieval can be seen in the constant measurement of thrust b (Ns^2).

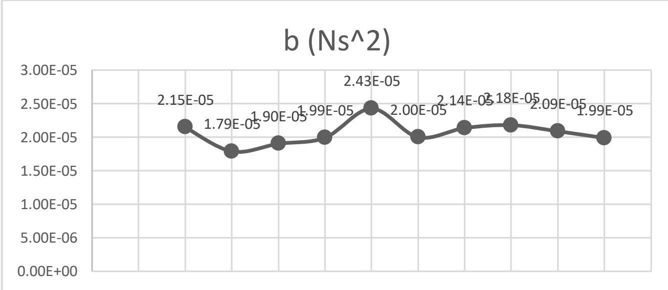

Figure 10. Result of Thrust factors b (Ns^2).

Then the motor will produce a moment which is directed opposite to the direction of rotation of the propeller. In hexacopter, the moment is utilized to rotate the body hexacopter on the z axis. The larger the engine speed, the greater the torque generated.

Just like the measurement of thrust, torque measurement is also using a tachometer with the touch system. So that reading becomes less accurate propeller rotation. This resulted in a lack of accurate data on the drag factor measurements d (Nms^2).

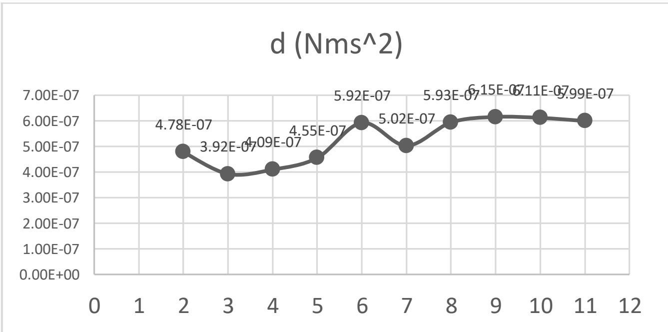

Figure 11. Result measurement of drag factor *d* (Nm^2).

A. Kinematics Calculation

Hexacopter fly with a trajectory as in figure 12 Takeoff and then move up and move forward and then move to the right. It is assumed that hexacopter move slowly with obstacles ignored.

Figure 12. Trajectory of hexacopter.

TABEL I. The parameters used in this calculation

Symbol	Description	Value
I_{xx}	Moment of inertia on x-axis	0.024 Nms^{-2}
I_{yy}	Moment of inertia on y-axis	0.024 Nms^{-2}
I_{zz}	Moment of inertia on z-axis	0.046 Nms^{-2}
J_r	Moment of inertia *propeller*	$0.103x10^{-6}$ Nms^2
B	Constant of thrust	$2.07x10^{-5}$ Ns^2
L	Distance of motor to the center of gravity	0.29 m
M	Mass of *hexacopter*	2.001 kg

With the throttle at 65%, hexacopter takeoff and moving upwards. No change in the angle of the x, y, and z in the body frame. So that the acceleration experienced by hexacopter obtained

$$F^B_{dorong} = b\sum_{i=1}^{6}\Omega_i^2$$

$$F^B_{dorong} = 151.37\ N$$

$$\begin{bmatrix}\dot{u}\\ \dot{v}\\ \dot{w}\end{bmatrix} = \begin{bmatrix}0\\ 0\\ 65.85\ ms^{-2}\end{bmatrix}$$

Hexacopter fly in the right direction with a roll angle of 0.175 radians and angular acceleration of 1.75 rad / s. Linear acceleration and angular acceleration experienced is.

$$F^B_{dorong} = 151.37\ N$$
$$\tau_{roll} = 0.541Nm$$
$$\Omega_r = 0$$
$$\begin{bmatrix}\dot{u}\\ \dot{v}\\ \dot{w}\end{bmatrix} = \begin{bmatrix}0\\ 1.706\ ms^{-2}\\ 0\end{bmatrix}$$
$$\begin{bmatrix}\dot{p}\\ \dot{q}\\ \dot{r}\end{bmatrix} = \begin{bmatrix}22.54\ rad/s^2\\ 0\\ 0\end{bmatrix}$$

B. Flight Experiments

Hexacopter fly with a trajectory as in figure 12. The height of the fly is limited to 5-10cm above floor level. Starting point is flown from point A to point B. Once flown, the movement trajectory hexacopter measured and recorded. Hexacopter trajectory can be seen in Figure 12.

The value of RMS (root mean square) of errors noted is 2:35 cm, farthest experienced deviation is 6:30 cm. This value is quite large. This happens because hexacopter fly in a state that is less stable and difficult to control.

Some factors That Can Interfere Stability Hexacopter *Propeller* is unbalance because of the *frame* is non-symmetrical.

V. Conclusions

Hexacopter successfully made in accordance with the design. Specifications hexacopter as described earlier in this part. The maximum lifting force that can be generated motor at a maximum rotation 521.34 rad / s was 5.4 N. The maximum moment that can be generated is 0:16 Nm. RMS of the error generated hexacopter during flight can be minimized.

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