VIBRATION ANALYSIS ON FRAME AND PROPELLER OF DRONE

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ABSTRACT

This paper explains the experimental vibration analysis of a quad copter Frame and Propeller. The paper discusses an analysis of the main vibration sources affecting this UAV and an experimental modal analysis of the main structural components of the quad copter Frame and Propeller. The resulting data is applied to a numerical analysis of the quad copter Frame and Propeller, for instance, locating low vibration regions where Propeller should best be mounted. The drone propeller is implemented using the commercially available computational fluid dynamics (CFD) solver, FLUENT. Numerical validation is compared with the available experimental validation for an advanced precision composites (APC) Slow Flyer propeller blade to determine the thrust coefficient, power coefficient, and efficiencies. The study uses unstructured tetrahedron meshing throughout the analysis, with a standard k-ω turbulence model. The Various Reference Frame model also used to consider the rotation of the propeller toward its local reference frame at 3008 revolutions per minute (RPM). Analysis show reliable thrust coefficient, power coefficient, and efficiency data for the case of low advance ratio and an advance ratio less than the negative thrust conditions.The use of theory on aerodynamics of quad rotors using the well-established momentum and blade element theories. As per robotics point of view, the theoretical development of the models for thrust and horizontal forces and torque are carried out in the body fixed frame of the quad rotor. Using momentum theory, the existence of a horizontal force along with its associated power can be calculated.

Keyword: APC slow flyer, Ansys, CFD fluent, Frame, Momentum theory , Propeller.

I. INTRODUCTION

There are various qualities to be fulfilled while designing the quad copter body frame, such as creating a best rigid body as light as possible and capable to carry load, also the mounting of electronic components, sensors and rotors. Quad copter's size and shape depends on its usage. To assist in the creation, modification, analysis, or optimization of the design Computer-Aided Design (CAD) is used. Quad copter frame size was developed first, so the type of rotor and propeller which will be used can be selected accordingly.Quad copter frame can be made from plastic, carbon fibre, aluminium and wood. The chosen H-frame size was (230mm*230mm) which was considered the right size to carry the desired load. The design use less number of bolts and screws especially in the H-frame because loose of screw and bolts caused by vibration when the quad copter is flying and the center of mass to place components and the sensor is in the middle. The magnitude of rotor's speed rotation and the type of propeller used will decides the magnitude of thrust. Thrust is the force exerted by a propeller which fly's a quad copter in the air. Knowing the magnitude of thrust produced by each rotor, the body frame strength and rigidity can be analyzed using Ansys software. Propeller with size (90 mm*45mm) was analyzed to study the effect of its airflow towards body frame. A propeller may be considered as a rotating Element that assembles air foils together, as compared to the cross-section of the wing of an aircraft.

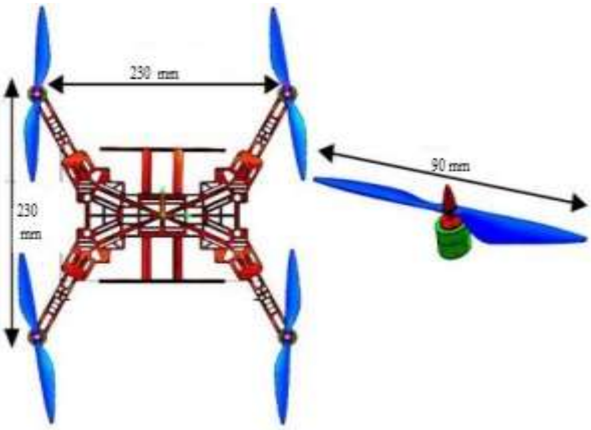

Fig.1. Body frame quad copter model

Generally propeller configuration having a minimum of two blades, attached together to the central hub. Thrust is generated to push the UAV forward through the air, by converting the rotation power from the shaft. According to Bernoulli's principle, due to the acceleration of the airflow, it causes a decrease of static pressure in front of the blade. By selecting the body fixed frame, we uses momentum theory to find thrust, horizontal force and torque.

II. MOTIVATION

These Quad copters are having so many applications due to

- No gearing required between the motor and the rotor
- No variable propeller pitch is required for alternating quadrotor
- Minimal mechanical complexity
- Low maintenance
- Less loads on the center plates

• Payload augmentation

III. LITERATURE REVIEW

1.1 QUADCOPTER RIGIDITY ANALYSIS

Newton's Law of Motion is used to calculate resulting thrust generated by propellers. 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

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

From this equation relationship between thrust, induced velocity and power in the rotor and propeller is explain.

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. Pressure force depends on the air density (ρ) and velocity of air (v_i). According to momentum conservation, the thrust on the disc is equal to the overall rate of increase of axial momentum of the air

$$T = \rho A v_i v_o$$

The propeller effects is a pressure change which draws the air in front of it and then pushes it out (accelerated by the propeller), represented by v_o. This means that the air velocity accelerated by the propeller is approximately twice of a maximum of the air velocity ($v_o = 2*v_i$; $v_i = ½* v_o$).

$$T = \frac{\pi}{8} D^2 \rho v_o^2$$

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). Magnitude of air flow and thrust produced is determined from propeller size and its angular velocity.[1]

Related to quad copter body frame, the amount of resulting thrust can be used to calculate the rigidity of the designed frame. The maximum resulting thrust was 26 (N) or equivalent with 2650 (gram-force) for one rotor in a quad copter.

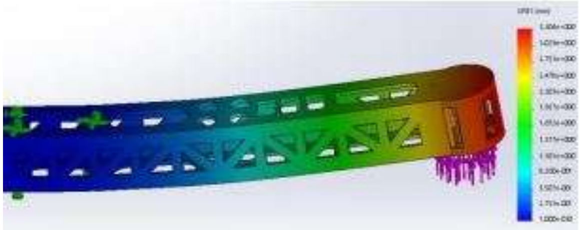

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Fig. 2. Wing frame displacement analysis

Fig. 2.Shows the maximum displacement which occurred on the rotor (1.5 mm) and on the center of wing frame (between 0.4 and 0.8(mm)). The material used is plastic (ABS) with an elastic modulus of 3000 (N/mm^2). This means the quad copter has a good rigidity with designed wing frame size. The total weight of the overall frame is 60 (gram).

1.2 MOMENTUM THEORY OF ROTORS

Glauert developed Momentum theory for rotary wing vehicles based on earlier work by Froude for aircraft propellers. This is one of the two most popular theories for propeller blade analysis. It is simple approach has made it the reference for modelling aerodynamic forces on rotors. The theory assumed a rotor as an actuator disc with the accelerating air forming a stream tube. The control volume as shown in Fig. 3 shows this stream tube.Glauert made some assumptions which are stated below,

- The rotor disc has an infinite number of rotor blades such that there is a uniform constant distribution of aerodynamic forces over the rotor disc.
- The rotor disc is an infinitely thin disc of area A which offers no resistance to air passing through it.
- The flow is irrotational and therefore no swirl is imparted to it.
- The air outside the stream tube remains undisturbed by the actuator disc.

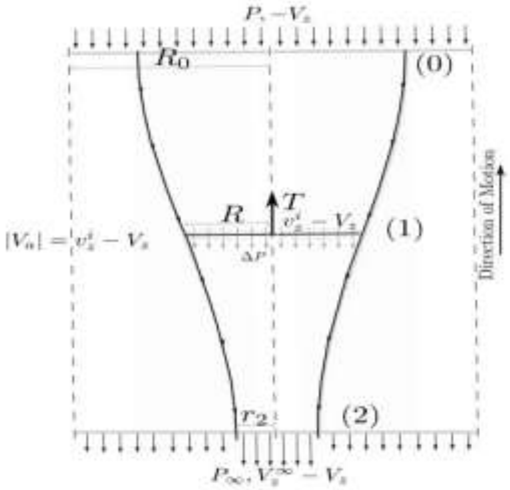

Fig. 3.Vertical stream tube for hover and axial analysis.

It is observed that the higher the disc loading, the more these assumptions hold. The disc loading (DL) is defined as DL = T/A. The quad rotor considered in this report (and quad rotors in general) has a higher disc loading than the majority of helicopters, indicates that momentum theory holds better for quad rotors than for helicopters.[2]

1.3 SMALL APC SLOW FLYER PROPELLER BLADE.

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Generally, the propeller used in drone is less than 24 inches in diameter. Thus, in the current study, the advanced precision composites (APC) Slow Flyer propeller is set as the standard design as it is one of the common blades used for UAVs, and due to the availability in experimental data.The APC Slow Flyer is a two-bladed propeller, with a fixed pitch and a diameter of 45 mm and 90 mm respectively. The propeller consists of thin airfoil profiles with a specific combination of a low Reynolds number Eppler E63 and a Clark-Y airfoil near the tip, inserted to form a sharp leading edge blade design, as shown in Fig. 4.

Fig.4 Standard APC Slow Flyer 90mm *45mm propeller blade.

The pitch of 45mm provides a pitch-to-diameter ratio of 0.5, which is common for an off-shelf Propeller type. The Reynolds number of the propeller is approximately 50804, which is defined by the rotational speed of 3008 RPM and a chord at a 75% blade station. The APC Slow Flyer used in this study, as shown in Fig. 4, is modelled using CAD software prior to Ansys. [3]

1.4 PROPELLER ANALYSIS

The propellers used in the quad copter rotors are fixed pitch, signifying that the pitch angle β, sometimes referred to as the blade angle, remains fixed. As the pitch can vary along the length of the propeller blade but cannot be adjusted, hence it should not be confused with constant pitch. The pitch angle determines the pitch of the propeller p, which is the distance that the propeller moves through the air for each revolution, as like a screw. Hence propellers are sometimes referred to as 'air screws'. This relationship can be described as, [4]

$$p = 2\pi r \tan\beta \qquad (1)$$

Where r is the distance along the blade where the specific pitch angle exists. Because of the variation that exists, a ratio is commonly used known as the pitch diameter ratio,

$$p/D = \pi x \tan\beta \qquad (2)$$

Where D is the diameter of the propeller and x is the relative radius of the blade section and may be represented as,

$$x = r/R \qquad (3)$$

Because of the variation of β and c throughout the length of the radius, the angle of attack α is also varied. This is can be shown graphically in Fig. 5.

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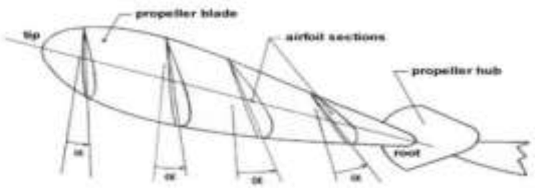

Fig. 5 Fixed pitch propeller geometry

In Figure 6, an infinitesimal cross section *dr* and a length r away from the center of the propeller was considered. The dashed line represents the zero lift line in the figure. The velocity V_E is the induced air velocity and enters the blade at an angle α to the zero lift line. The velocity V is the advance velocity of the propeller and the velocity ωr is the velocity due to rotation. The angle Φ is the angle of resultant flow. The dimensionless coefficient of lift C_L is dependent on angles α, β and Φ and the coefficient of drag C_D is a function of C_L and Mach and Reynolds numbers. The lift dL generated is always orthogonal to the line of zero lift. The thrust dT, which is the effective upward force perpendicular to the plane of rotation, is a component of dL. The drag dD is the force acting adjacent to the airfoil and the force dF_Q is the component of dD which creates the drag moment dQ where,

$$dQ = dF_Q\, r \qquad (4)$$

The local lift and drag may be expressed as,

$$dL = \frac{1}{2}\rho V_E^2\, c C_L dr \qquad (5)$$

$$dD = \frac{1}{2}\rho V_E^2\, c C_D dr \qquad (6)$$

Where, ρ is the density of air. Vortex theory was analysed to determine the drag moment and thrust. In the same manner in which a wing works, the aerodynamic lift on a propeller blade can be related to a bound circulation Γ around the blade, as shown in Figure 6. This bound circulation may be expressed as,

$$\Gamma = \frac{1}{2} c C_L V_E \qquad (7)$$

Using the change in bound circulation, the local thrust and drag moments are,

$$dT = \rho\,(\Omega - \omega)\, r d\Gamma \qquad (8)$$

$$dQ = \rho\,(V - v)\, r d\Gamma \qquad (9)$$

Where, Ω and V are the global rotational and advance velocities respectively. From this, the local efficiency of the propeller can be found,

$$\eta_{local} = \frac{V dT}{\Omega dQ} \qquad (10)$$

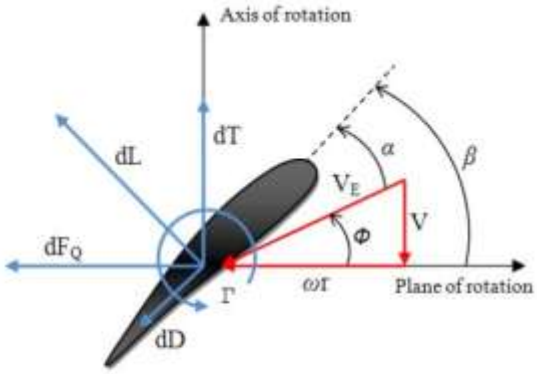

Fig. 6. Vector diagram for a section dr at length r away from centre of the propeller

To determine the overall efficiency of the propeller, a ratio of the product of the thrust and advance velocity and the power P must be found.

$$\eta_{overall} = \frac{VT}{P} \tag{11}$$

However, the thrust and power may be represented as,

$$T = \rho C_T D^4 n^2 \tag{12}$$

$$P = \rho C_p D^5 n^3 \tag{13}$$

It must be noted that D here refers to the rotor diameter and not drag. From this, the efficiency may be represented as,

$$\eta = \frac{V}{nD}\frac{C_T}{C_P} \tag{14}$$

The velocity ratio in this expression is known as theadvance ratio J,

$$J = \frac{V}{nD} \tag{15}$$

IV. QUADCOPTER BODY FRAME ANALYSIS RELATED TO PROPELLER.

In body frame design, propeller's size is determined by the distance between rotors. Magnitude of airflow and thrust produced will be determined from propeller's size and its angular velocity. Airflow variations will cause unexpected aerodynamic forces through changes in thrust conditions. The opposite pair of the propeller will rotate in the same direction, as shown in Fig. 7. There is a limitation on the maximum size of the propeller that can be used based on the magnitude of airflow produced by each rotor and the maximum torque of rotor. It is better to design the body frame to attain quad copter flight stability with respect to space area, and have control surface together with the aerodynamic, shapes of the rest of the airframe. The quad copter will move with the air mass when the air mass moves relative to spatial coordinates

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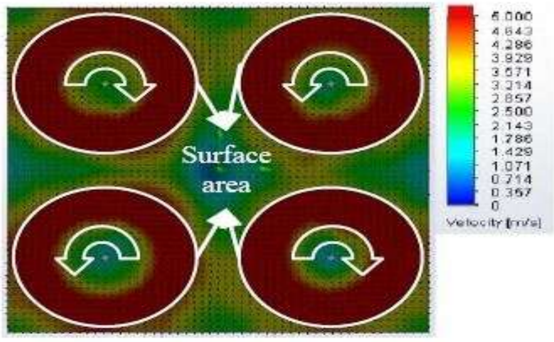

Fig. 7 Isosurface airflow around propeller

Based on the specification of the rotor used, the torque generated can be measured, which amount is 520 (rpm/v) and max voltage used is 19 (V). This means the rotor's maximum velocity is 9880(rpm). If there are four rotors with similar maximum velocity and with a propeller size 90x45 (mm), then the maximum wind velocity is 5 (m/s) on each propeller. In the chord line/coefficient thrust of the propeller the biggest wind velocity is occurred. Besides that, on the outside surface area of propeller rotation airflow is also produced, which is between 2.5 and 4 (m/s). Fig. 8 Shows the Isosurface airflow occurred between two propellers with 9880 (rpm).

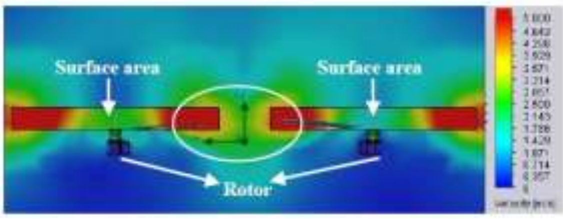

Fig. 8 Isosurface airflow between propellers with 9880(rpm)

The airflow velocity occurred between two propellers by maximizing the propeller's speed rotation, is between 2 and 3.5 (m/s). If the voltage used on the rotor is 12 (V), then the rotation movement generated is 6240 (rpm) and the airflow around propeller can be seen in Fig. 9.

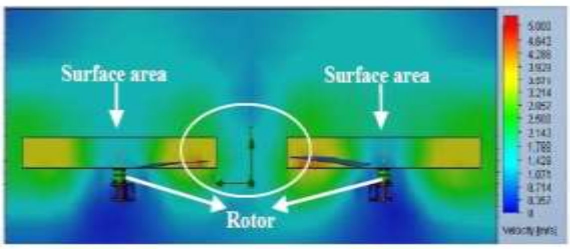

Fig. 9 Isosurface airflow between propellers with 6240 (rpm)

V. ANSYS RESULTS

1.1 Analysis of Quadcopter Frame

The analysis carried out is Structural Analysis. Load applied is 20N i.e. the approximate load for lifting a assembly using a Quadcopter. Applying a load of 20N and performing the structural analysis we have obtained equivalent stress which is within the limits.

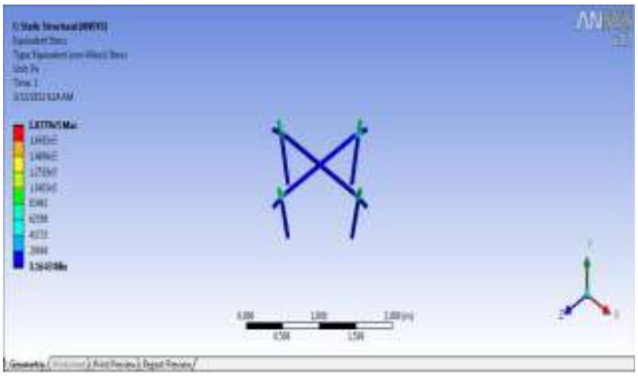

Fig.10. Analysis of Quadcopter Frame

The Ultimate Tensile Strength of Structural Acrylonitrile Butadiene Styrene (ABS) is 44 e+006 Pa. The Max equivalent stress that is obtained is 1.54 e+004 Pa. Hence the Frame is safe.

1.2 Analysis of Propeller

The propeller is also analysed using the structural analysis. For the analysis of Propeller it is given a rotational velocity of 9880rpm and the analysis is performed. The equivalent stress obtained is within the limit.

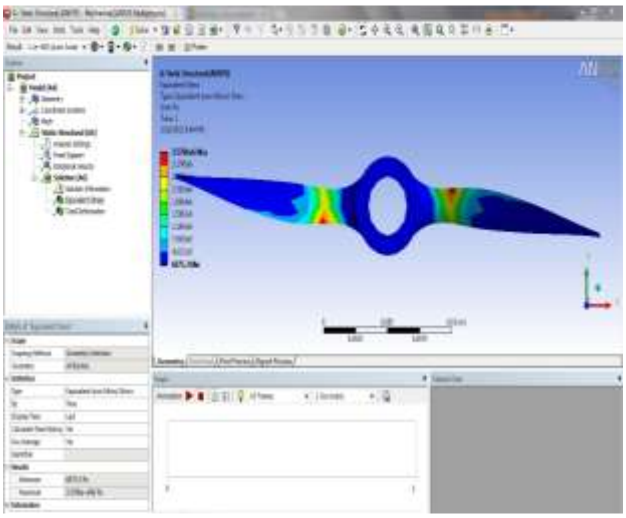

Fig.11 Analysis of Propeller

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The Ultimate Tensile Strength of Acrylonitrile Butadiene Styrene (ABS) is 44 e+006 Pa. The Max equivalent stress that is obtained is 3.75 e+005 Pa. Hence the Propeller is safe

VI. CONCLUSION

Ansys simulations used in this study successfully replicated the experimental results, which may significantly improve computational accuracy. It is desirable to design the pitch angle for best performance at take-off, due to the rotorcraft being propelled upward, where the advance velocities are low. Using the airfoil section S7075 the propeller is designed. Design is carried out by importing the airfoil section onto the datum planes. Using the Ansys workbench software Analysis of the Propeller and Frame are carried out and the results obtained are within the limits. For analyzing the propeller structure Ansys Workbench is the most efficient software. Hence, to achieve optimal aerodynamic performance, the only option would be to design a propeller to suit the specific application of high thrust upward propulsion.

VII. ACKNOWLEDGEMENT

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