Introduction to Multicopter Design and Control

Lesson 03 Airframe Design

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Preface

What should be taken into consideration when designing the airframe of a multicopter?

Outline

1. Configuration Design

2. Structural Design

3. Summary

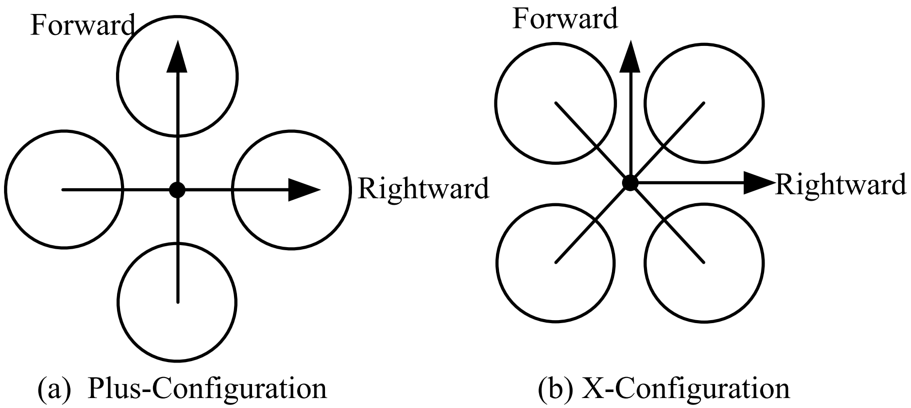
1. Configuration Design

□ Fuselage Configuration

(1) Cross configuration

According to the head direction, there are Plus-configuration and X-configuration

X-configuration multicopters are more popular, because they have higher maneuverability, and can avoid the occlusion of forward field angle.



(a) Plus-Configuration (b) X-Configuration

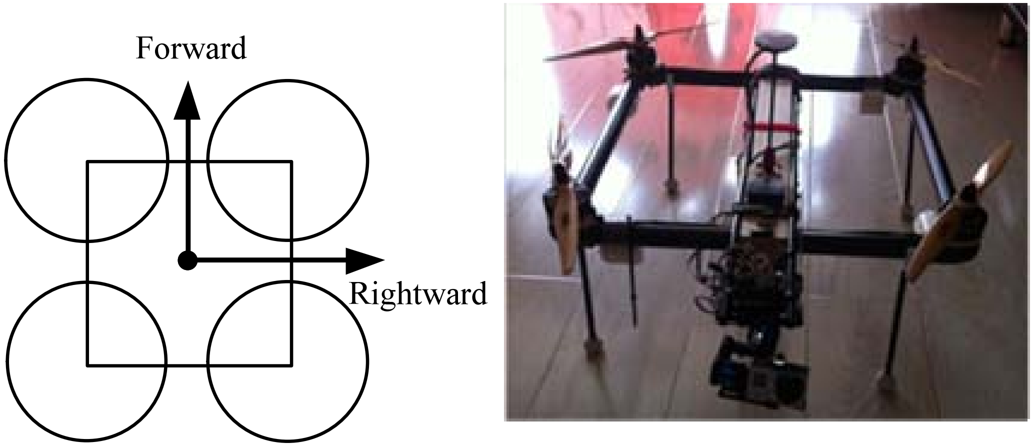
Fig3.1 The common configurations of multicopters

1. Configuration Design

Fuselage Configuration

(2) Ring configuration

- The ring configuration can be treated as a whole, which is more rigid than the traditional cross fuselage. It can reduce the vibration produced by the rotors more efficiently.
- The cost is that the fuselage is heavier than the cross form, which may reduce performance.



(a) Schematic diagram **(b) Picture of a real multicopter**

Fig 3.2 Quadcopter with ring configuration

1. Configuration Design

☐ Propeller Mounted

(1) Common form & co-axis form

1) Advantages of co-axis form

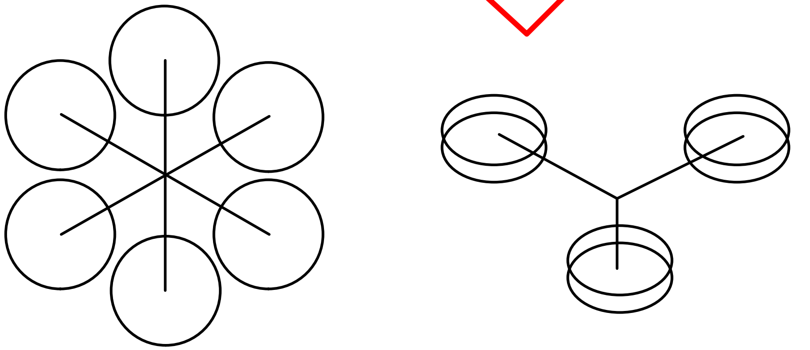
- Increase lift without increase size
- Prevent cameras from occlusion

2) Attentions

- Co-axis form may reduce the efficiency of the single propeller, approximately equivalent to 1.6 propellers as single-propeller mode.
- According to experiment [1], recommend

$$h / r_{\mathrm{p}} > 0.357$$

[1] Bohorquez F. Rotor hover performance and system design of an efficient coaxial rotary wing micro air vehicle [Ph. D. dissertation], University of Maryland College Park, USA, 2007.



Two motor roll in opposite direction to offset the gyroscopic moments

(a) Common form (b) Co-axis form with two propellers

Fig 3.3 Common form and co-axis form

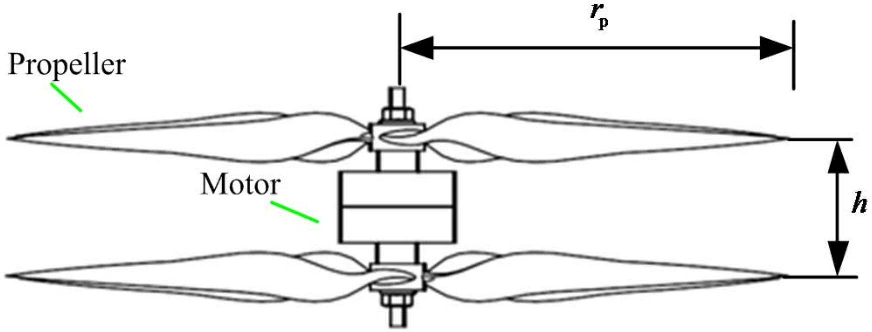


Fig 3.4 connection and geometry a co-axis form

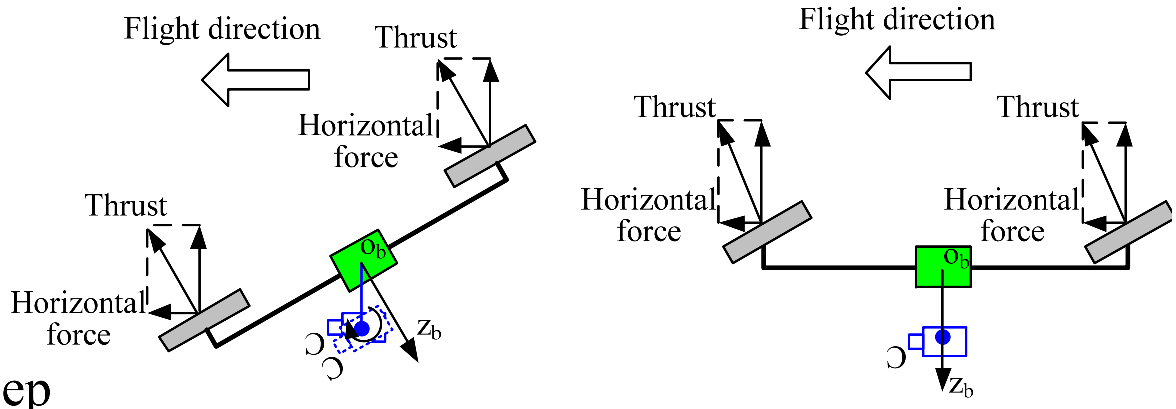
1. Configuration Design

Propeller Mounted

(2) Angle of propeller disc

1) The disc is horizontal

- Simple
- Camera stabilizer rotate to keep horizontal



(a) The disc is horizontal (b) The disc is not horizontal

Fig 3.5 horizontal disc and non-horizontal disc in forward flight

2) The disc is not horizontal

- At least six rotors（why? ）
- No need for camera stabilizer

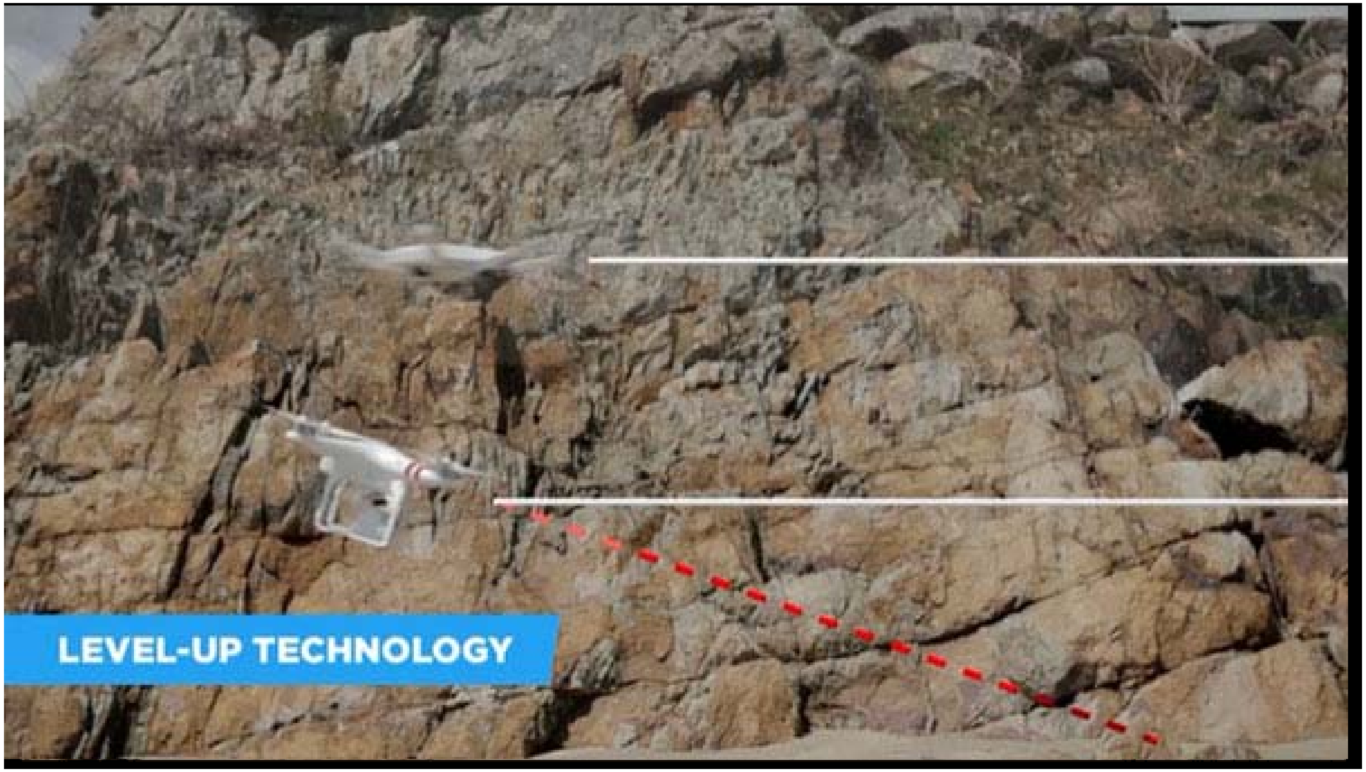
Fig 3.6 Non-horizontal disc Hexacopter CyPhyLVL1

1. Configuration Design

□ Propeller Mounted

(2) Angle of propeller disc

Video: CyPhyLVL1 flying video



1. Configuration Design

☐ Propeller Mounted

(3) Motor facing downward and upward

DJI Phantom

Zerotech Xplorer

Ehang Ghost

Xaircraft XMission

Motors facing upward

1) Producing lift force

2) Protecting propellers in landing phase

3) Giving a wider camera's view

Motors facing downward

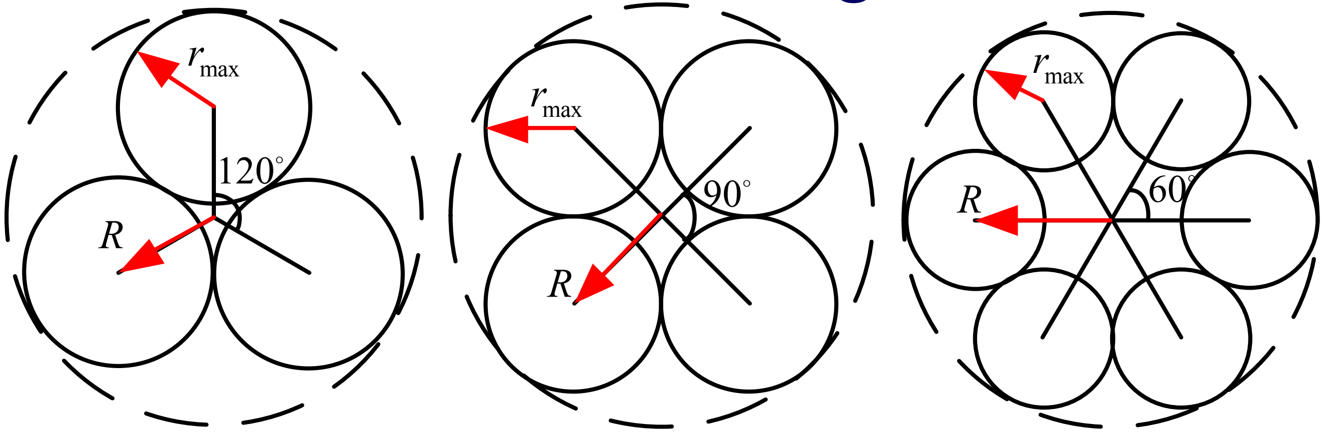
1) Producing thrust force

2) Protecting motors against rain

3) Ensuring a more accurate measurement of barometer

1. Configuration Design

☐ Propeller Radius and Fuselage Radius



(a) Y6-configuration hexacopter (b) Quadcopter (c) Hexacopter

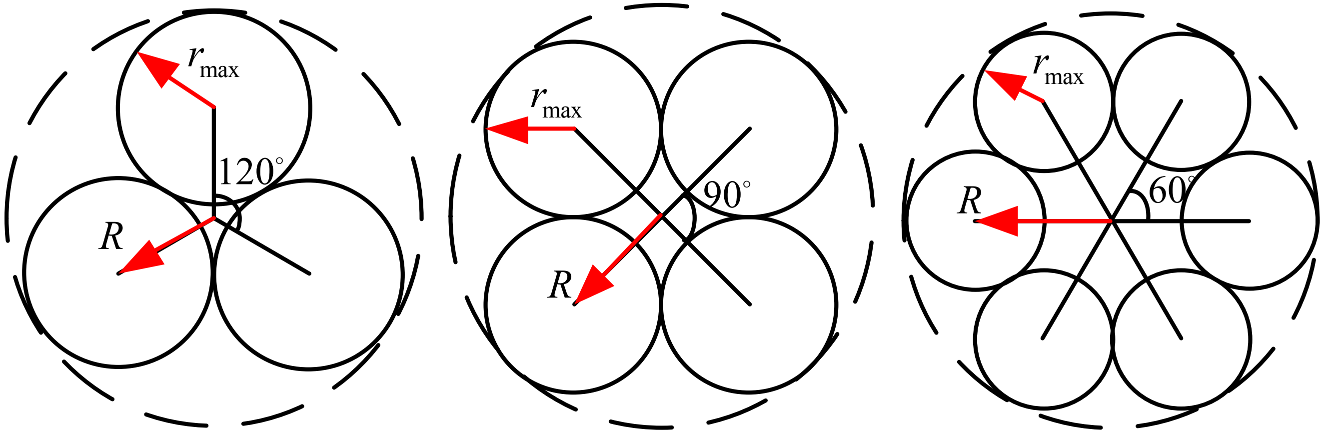
Fig 3.7 Multicopters with different configurations and their geometry parameters

The relationship between airframe radius R and the maximum radius of a propeller r_{max} is denoted by (θ is the angle between two arms, n_{r} is the number of arms)

$$R = \frac{r_{\max}}{\sin\frac{\theta}{2}} = \frac{r_{\max}}{\sin\frac{180^\circ}{n_{\mathrm{r}}}}$$

1. Configuration Design

☐ Propeller Radius and Fuselage Radius



(a) Y6-configuration hexacopter (b) Quadcopter (c) Hexacopter

Fig 3.7 Multicopters with different configurations and their geometry parameters

Experiment [2] shows, when the space between propellers varies from $0.1r_{\max}$ to $r_{\max}$, airflow has little effect on the vehicle performance. Hence, to make a multicopter more compact without losing much efficiency, the propeller radius r_{p} can be obtained

$$r_{\max} = 1.05r_{\mathrm{p}} \sim 1.2r_{\mathrm{p}}$$

[2] Harrington A M. Optimal Propulsion System Design for A Micro Quad Rotor [Master dissertation]. University of Maryland College Park, USA, 2011.

1. Configuration Design

☐ Relationship Between Size and Maneuverability

Reducing the size of a multicopter will reduce its inertia and payload, and finally influence the maximum angular acceleration a and linear acceleration.

$$\begin{aligned} T_{\rm p} &= \left(\frac{1}{2\pi}\right)^2 C_{\rm T}\rho\varpi^2\left(2r_{\rm p}\right)^4 \\ M_{\rm p} &= \left(\frac{1}{2\pi}\right)^2 C_{\rm M}\rho\varpi^2\left(2r_{\rm p}\right)^5 \end{aligned} \Rightarrow \left\{\begin{array}{c} T \sim T_{\rm p} \\ M_{\rm pitch,roll} \sim T_{\rm p}\cdot R \\ M_{\rm yaw} \sim M_{\rm p} \end{array}\right. \Rightarrow \left\{\begin{array}{l} T \sim \varpi^2 R^4 \\ M \sim \varpi^2 R^5 \end{array}\right. \Rightarrow \begin{aligned} a &= \frac{T}{m} \sim \frac{\varpi^2 R^4}{R^3} = \varpi^2 R \\ \alpha &= \frac{M}{J} \sim \frac{\varpi^2 R^5}{R^5} = \varpi^2 \end{aligned}$$

$$m \sim R^3, J \sim R^5$$

$T_{\rm p}$, $M_{\rm p}$: the propeller thrust and torque, T, M :the total thrust and torque， ω: propeller speed, R: airframe radius, J: the moment of inertia of multicopter, $r_{\rm p}$: the propeller radius。

(1) Mach number ("~" means under the same order of magnitudes)

$$\varpi \sim 1/r_{\rm p} \Rightarrow a \sim \frac{1}{R}, \alpha \sim \frac{1}{R^2}$$

(2) Froude number

$$v_{\rm b}^2/Rg \sim \varpi^2 r_{\rm p}^2/Rg \sim 1 \Rightarrow \varpi \sim 1/\sqrt{r_{\rm p}} \Rightarrow a \sim 1, \alpha \sim \frac{1}{R}$$

Size ↑

Maneuverability↓

1. Configuration Design

☐ Position of the Center of Gravity(CoG)

(a) CoG is low

(b) CoG is high

Fig 3.8 Two ways of camera installation of Freefly quadcopter

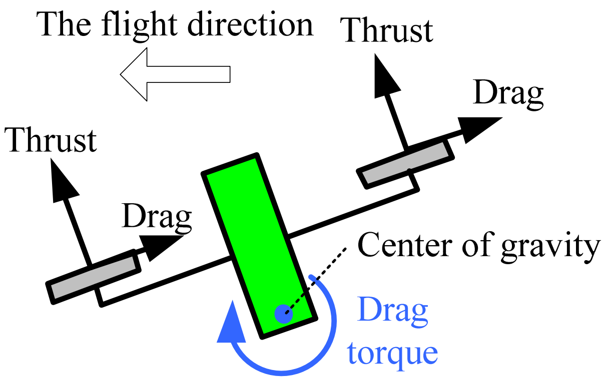
- When designing a multicopter, it is necessary to put the CoG of the multicopter on the central axis.
- Another task is to determine whether the CoG should be above or below the propeller disk plane?

1. Configuration Design

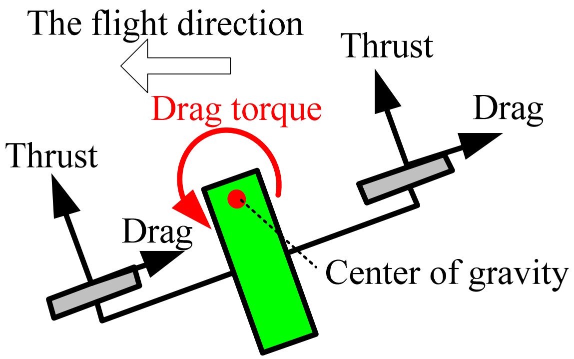
□ Position of CoG

(1) Forward flight situation

- As in the figure, the induced airflow will derive the drag during flight.
- As shown in figure (a), if the CoG is under the propeller disk, the drag torque will make the pitch angle tend to zero.
- As shown in figure (b), if the CoG is above the propeller disk, the drag torque will cause the increase of the pitch angle until the multicopter is turned over.



(a) Forward flight with low CoG



(b) Forward flight with high CoG

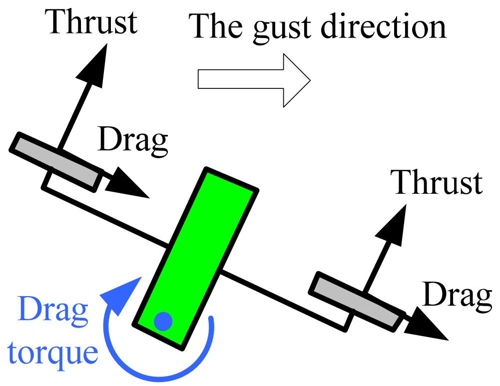
Fig 3.9 Forces on multicopters

1. Configuration Design

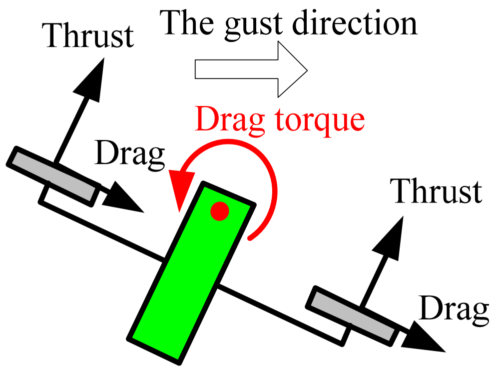
☐ Position of CoG

(2) Wind interference situation

- When gust blows, the induced airflow will give rise to the drag.
- As shown in figure (c), if the CoG of a multicopter is under the propeller disk, then the drag torque will cause the increase of the pitch angle until the multicopter is turned over.
- As shown in figure (d), if the CoG is above the propeller disk, the drag torque will make the pitch angle turn to zero.



(c) Wind interference with high CoG



(d) Wind interference with low CoG

Fig 3.9 Forces on multicopters

1. Configuration Design

☐ Position of CoG

(3) Conclusion

- No matter where the CoG is, the multicopter cannot be stable. Need the flight controller to maintain balance.
- If the position of the CoG is far above the propeller disk, namely a certain dynamic mode of the multicopter will be very unstable.
- Thus, it is suggested that the CoG should be just located at the propeller disk plane, or a little under it if necessary. More detail can refer to [3].

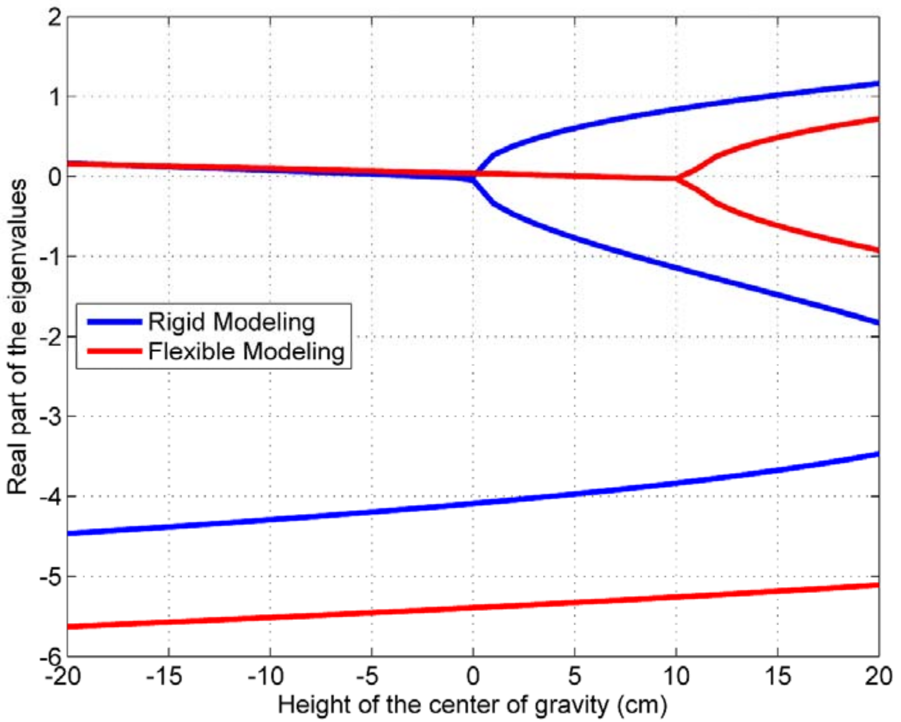


Fig 3.10 Location of CoG v.s. stability[3,Fig.7]

[3] Bristeau P J, Martin P, Salaun E, et al. The role of propeller aerodynamics in the model of a quadrotor UAV. In: Control Conference (ECC). European: IEEE, 2009. 683-688

1. Configuration Design

□ Autopilot Installation Position

Owing to the centrifugal acceleration and tangential acceleration, if the autopilot is far from the CoG, it would produce an error in the accelerometer measurement, which is also called “lever-arm effect”.

(1) Standard installation position.

Generally, the location should be within a few centimeters near the center of the aircraft, and should be horizontal with motors.

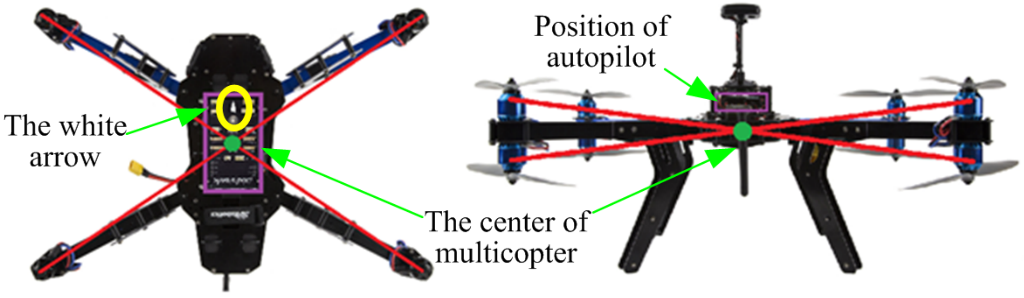


Fig 3.11 Installation position of an autopilot

(2) Substitution

Pixhawk/APM2 autopilot can be installed in the rack over 30° and then the standard installation position is retrieved by using a corresponding calibration algorithm.

1. Configuration Design

☐ Aerodynamic Configuration

The aerodynamic design aims to decrease the drag during flight. Drag can be divided into four types:

(1) frictional drag

(2) pressure drag

(3) induced drag

(4) interference drag

It is related to windward area, the larger the windward area, the greater the pressure drag. The three objects in figure below have the same windward area, streamline is subject to the least drag.

To reduce drag, it is important to consider the aerodynamic design. decrease the maximum windward area, use streamline, and the shape should be smooth as possible.

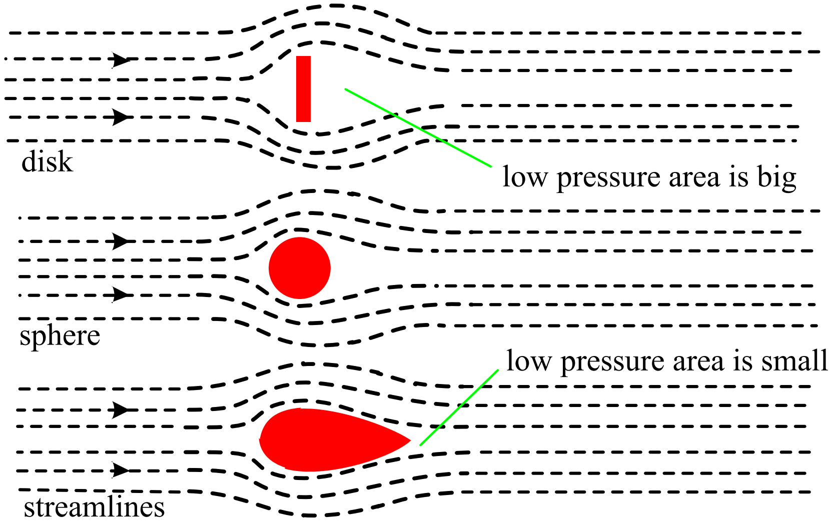


Fig 3.12 Pressure drag of three objects

1. Configuration Design

□ Aerodynamic Configuration

Design suggestion:

(1) The angle of pitch should be considered to decrease the maximum windward area.

(2) A streamline body should be designed.

(3) The relative position of each component should be taken into account. The joint of components and the vehicle surface should be as smooth as possible.

(4) Use CFD method to optimize the drag coefficient and the shape.

(a) DJI Inspire 1

(b) Xaircraft Xmission

(c) Microdrones MD4-3000

(d) DHL Parcelcopter

Fig 3.13 Quadcopters with well aerodynamic design

2. Structural Design

☐ Design Principles of Airframe

(1) The strength and rigidity satisfy the load requirement, little shaking and bending as possible. The structure is able to support ultimate loads without failure.

(2) After other necessary requirements have been achieved, the total weight is as light as possible.

(3) The proportion of the length, the width and the height of a multicopter is proper, the structural layout is suitable.

(4) Aesthetic and durable.

2. Structural Design

☐ Anti-Vibration Design

(1) Significance of anti-vibration

1) Accelerometers are used for the estimation of the position and the attitude, which is of great importance. However, it is very sensitive to vibration. Concretely:

- Acceleration is directly related to the estimation of the attitude angles.
- The data of the acceleration is fused with the barometer and the GPS to estimate the multicopter position.

2. Structural Design

□ Anti-Vibration Design

(2) Main source of vibration

1) Airframe

Recently, the concept of wearable quadcopters has received more and more attention, such as Nixie, which requires that its airframe is flexible and easily transformed, which seems to violate the principles mentioned above. (How to solve?)

These problems should be considered in the design. For example, the airframe can be blended unidirectionally, opposite to the direction of the thrust and moments. Moreover, the airframe is anti-torsion and anti-bending in the direction of the thrust.

(a) Flod (b) Unfold

Fig 3.15 Nixie conceptual wearable quadcopter

2. Structural Design

☐ Anti-Vibration Design

(2) Main source of vibration

2) Motor

- Motors work smoothly;
- The rotor holder should be coaxial with the bearing and the center of the propeller, thus getting rid of the eccentric force produced when motor is rotating;
- All rotors are in balance.

2. Structural Design

☐ Anti-Vibration Design

(2) Main source of vibration

3) Propeller

- Propellers are in balance (refer to Lesson 2) ;
- Propellers should be matched with the airframe size and the multicopter weight; and there are similar toughness when rotating both clockwise and anticlockwise;
- Carbon fiber propellers are suitable.;
- Carbon fiber propellers are with high stiffness, but the hidden danger to personnel exists when propellers are in rotation
- The low-speed large propeller is more efficient than the high-speed small one, but the large propeller will cause more vibration in amplitude.

2. Structural Design

☐ Anti-Vibration Design

(3) Constraint of vibration strength

1) the lateral vibration strength is less than 0.3g, while the longitudinal vibration strength is less than 0.5g.

2) the vibration strength on all axes is better, which is bounded less than 0.1g.

After all factors above have been taken into account, the left problem is to consider methods for vibration damping and isolating.

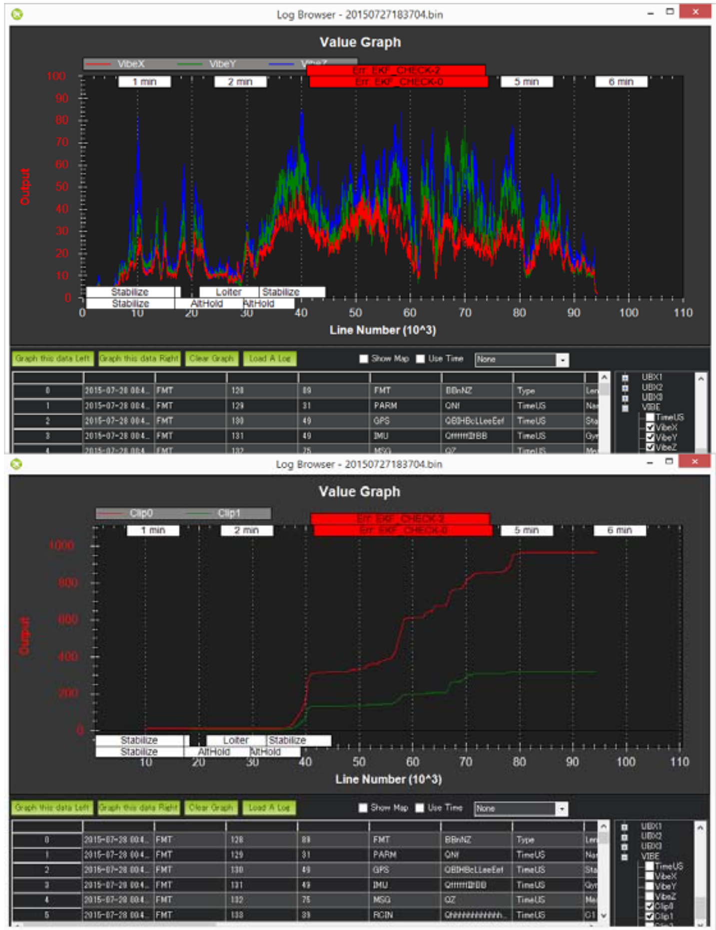


Fig 3.16 Position estimation under strong vibration, From: http://copter.ardupilot.com

2. Structural De

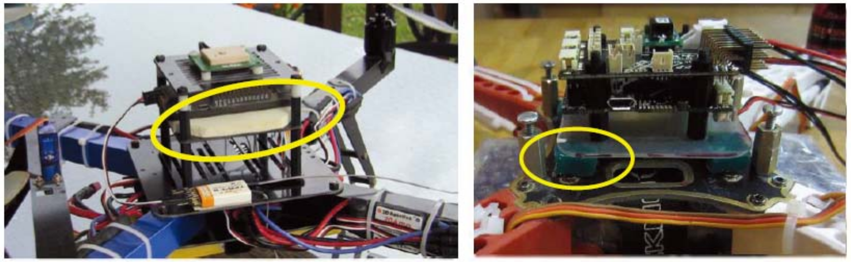
☐ Anti-Vibration Design

(4) Vibration damping between autopilot and airframe

1)Traditionally, the double-side foam type and the nylon button are used to fix the autopilot.

2) In many cases, as the flight controller has small mass, the double-side foam type and the nylon button are not effective. The tested feasible methods are to use the foam, the gal pad, the O-ring and the earplug.

3) At present, there also exist dampers for the autopilot in market, is made of two glass fiber frames, four damping balls and two foam pads.


(a) Foam (b) Gel pad

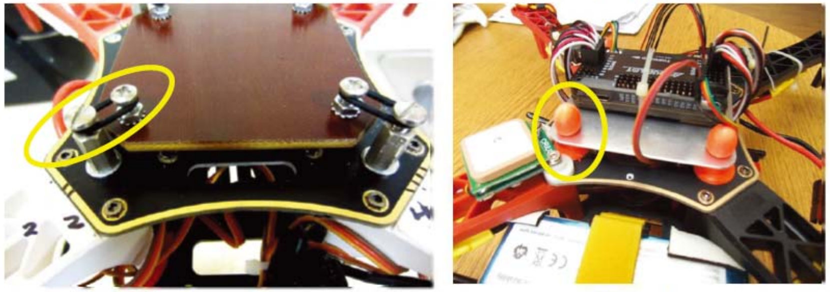

(c) O-ring (d) Earplug

Fig 3.17 Anti-Vibration methods: http://ardupilot.com/

Fig 3.18 A flight controller damper

2. Structural Design

□ Noise Reduction Design

(1) Main harm of propeller noise

1) If the body exists in the sound field produced by propellers, some sensors may become invalid because of the influence of noise;

2) Noise will affect the surrounding flight environment, and cause pollution, especially when multicopters are over residential areas;

3) The body vibration and the acoustic fatigue induced by the noise may seriously influence the safety of aircraft.

2. Structural Design

☐ Noise Reduction Design

(2) Propeller sound generating principle

1） Tone noise. Primary sources of tone noise depend on the rotor tip speed and the flow conditions in which the propeller is operating. At low speeds the dominant source of sound is caused by the unsteady pressure on the blade surface. There are many effects that can affect the blade loading. If the propeller is operating in a completely clean inflow, which is rarely the case, then the blade loading is steady in blade based coordinates but the component of the force in the direction of the observer varies as the blade rotates.

2） Broadband propeller noise. Broadband rotor noise is always caused by random variations in blade loading resulting from the interaction of the blades with turbulence.

2. Structural Design

☐ Noise Reduction Design

(3) Noise reduction method

1) Propeller diameter and Blade sweep. Increasing blade sweep or diameter can reduce noise because the blade tip is significantly reduced;

2) Blade thickness. Thickness noise is important at high tip Mach numbers. To reduce the total volume of blades can reduce the relative thickness and length of propeller-blade profile. Then thickness noise can be greatly reduced;

3) Blade count. For a given thrust requirement, increasing the number of propeller blades and decreasing the outside diameter of propeller blades can reduce the relative Mach number of blades' tip, and therefore reduce the noise radiated by propeller;

4) Blade shape and airfoil section. It is possible to reduce noise by designing a blade to move the peak of aerodynamic loads from span distribution to internal diameter direction. In general, these parameters have a much larger effect on the aerodynamic performance of the propeller than they have on the noise.

3. Conclusion

(1) The design requirement should be further taken into consideration. For example, the hexacopter CyPhy LVL1 is quite distinctive for its nonhorizontal propeller disks

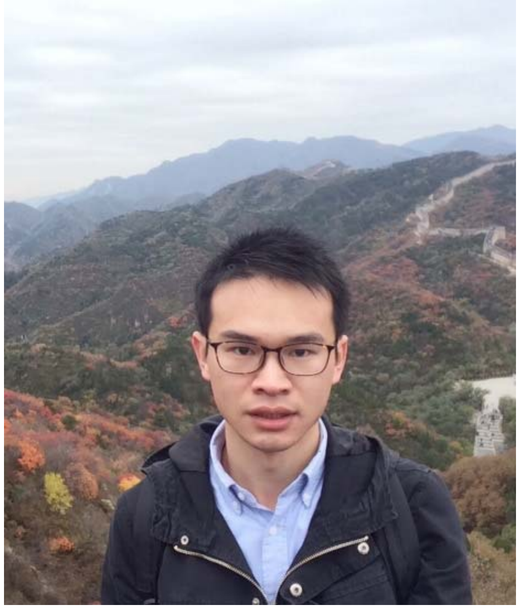
(2) Since the vibration is derived from the airframe transformation, and the asymmetry of motors and propellers, the airframe should be chosen as rigid as possible, and also high-quality motors and propellers should be chosen.

(3) In order to reduce noise, effective methods should be implemented. These can be achieved eventually by designing new propellers.

In this lesson, some design principles without specific design methods are simply shown. The problems of how to design a multicopter to minimize the drag, vibration and noise are deserved to research in the future.

Acknowledgement

Deep thanks go to



Xunhua Dai

for material preparation

Thank you!

All course PPTs and resources can be downloaded at
http://rfly.buaa.edu.cn/course

For more detailed content, please refer to the textbook:

Quan, Quan. Introduction to Multicopter Design and Control. Springer, 2017. ISBN: 978-981-10-3382-7.

It is available now, please visit http://www.springer.com/us/book/9789811033810