32nd Congress of the International Council of the Aeronautical Sciences
ICAS 2021 SHANGHAI
September 6-10, 2021
Pudong Shangri-La, Shanghai, China

NUMERICAL STUDY OF QUAD-ROTOR AIRCRAFT PERFORMANCE UNDER ADVERSE SITUATIONS

Tung Wan and Meng-Han Tsai

Department of Aerospace Engineering, Tamkang University, Taipei, Taiwan, Republic of China

Abstract

Unmanned Aerial Vehicles or UAVs are becoming more popular nowadays, and in-depth study of quad-copter UAV falls into detrimental situations required more investigations. In this work not only the aerodynamic parameters of quad-copter, but also the physical phenomenon for quad-copter flying under severe weather conditions are numerically simulated. An APC 10x4.7 rotor is first chosen as the validation benchmark case. Due to recent aviation safety concerns, the free-fall situation of quad-copter will be our major concern, and the worst realistic situations under severe weather condition are simulated, such as flying in the heavy rain and different typical gust wind conditions, for both the quad-copter hover and forward flight situations. It is found that the heavy rain effect is not as severe as the downdraft or the horizontal gust wind situations. It is hoped that this research can help the quad-copter UAV industries and academia to understand more about how adverse situations' impact on quad-copter performance.

Keywords: Quad-copter, Terminal Velocity, Heavy Rain, Gust Wind, Performance

1. Introduction

Due to fuel consumptions and costs, people have tried finding more efficient, eco-friendly, and also safer aerial vehicle. Unmanned aerial vehicles (UAVs) has been more and more popular, especially for quad-copter as shown in Figure 1 [1]. Quad-rotor unmanned aircrafts have seen a rapid rise in production and utilization in the past few years. Similar to helicopters, quad-copter has made progress to become much safer, easier to control and could accommodate stronger gust wind. For these advantages, quad-copter can be used in different missions, for example, it can search and rescue people during disasters or carrying cargos as needed. But unlike fixed-wing aircraft or helicopters which has existed for some time and we have deeper understanding in them, the development of quad-copter seems just started.

Figure 1 DJI Phantom quad-copter. [1]

As the use of these vehicles continues to increase, researchers have emerged concerns of their designs, handling qualities, and control, especially under severe weather conditions. By studying their performance, it is possible to develop models that can accurately predict the performance and even its normal or crashing trajectories. Safety is always the first priority in aviation industry, consider there's no need for on-broad pilot to fly the quad-copter, it will still be very dangerous if quad-copters fall from higher altitude. According to FAA's report [2], a 1 *kg* quad-copter falling from 500 *ft* height is enough to serious injured a person or even to death. Needless to say, there are many quad-copters or drones today on the market that are much heavier than 1 *kg*. To prevent this kind of tragedy and monitor the handling ability of personnel who fly drones, the free-fall situation is becoming one of the most important and urgent issues currently in the civil aviation arena. A detailed research done by Arterburn, et al. [3] showed the degree of damage if quad-copters falls on different land area and different impact spots on a human's body would do.

However, when operating a quad-copter during severe weathers the most important factor will be the low level gust wind and the rain conditions, especially if it's used for disaster relief mission. When quad-copter encounters gust wind it might cause the quad-copter into a free-fall, thus the aerodynamic effect and its performance change such as the drag or lift forces and flight attitude should be fully investigated under these different severe weather conditions.

2. Research Background

2.1 Aerodynamic Definitions of Quad-copter

The aerodynamic characteristics of a quad-copter are different from traditional aircrafts. One obvious difference is that the traditional aircraft gain lift through the fixed wing, but for quad-copter instead of the wings, it gains lift through rotating the propellers. The dimensionless power and thrust coefficients C_p and C_T are defined through definitions [4], where ρ is air density, *n* or Ω is rotational speed or angular velocity and *D* the rotor diameter:

$$C_p = \frac{P}{\rho n^3 D^5} \tag{1}$$

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

Or the thrust *T* and thrust coefficient, C_T, can also be defined as [5]:

$$C_T = \frac{T}{\rho A (\Omega R)^2} \tag{3}$$

The total drag coefficient of quad-rotor is formulated as:

$$C_D = \frac{D}{\rho A (\Omega R)^2} \tag{4}$$

Here Ω is rotating speed in *rad/s*, *R* is radius distance and *A* represents the rotor disk area.

2.2 APC 10x4.7 Propeller and the Full-Size Quad-copter

According to Hairuniza and Parvathy [6], usually, the propeller used on UAVs would not be longer than 24 *in* in diameter. The APC Slow Flyer propeller has two blades with a fixed pitch and a diameter of 10 *in* or 0.254 *m*, and is chosen as our benchmark test configuration. The APC 10x4.7 propeller blade is showing in Figure 2.

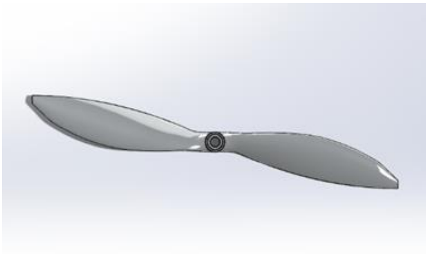

Figure 2 Standard APC Slow Flyer 10 x 4.7 propeller blade.

Figure 3 Current full-size configuration of quad-copter.

Our quad-copter is constructed as an imaginary quad-copter; combine with the APC 10x4.7 propeller configuration but is 1.3 times larger than the original prototype. The main body of our quad-copter has the similar shape as the "DJI Phantom" [1], the width of the body is 447 *mm* and 96.55 *mm* height at the thickest center location. The geometry details are shown in Figure 3.

2.3 Gust Wind Phenomenon

Gust wind means the wind speed varies in a short time, its duration should be less than 20 second. Gust occurs as part of the natural fluctuation of the wind speed within a 10-minute period of stationary wind condition, which without implying a change in the mean wind speed. Let A represents magnitude and f_g the gust frequency, then a simple freestream gust wind speed can be express as:

$$V(t) = V_\infty(1 + Asin(2\pi f_g t)) \tag{5}$$

Due to the inherent nature of the atmosphere, realistic gust wind profiles are fundamentally different in the horizontal and vertical directions, and for quad-copter operation environment it is the low level planetary boundary layer wind profiles that we are most interest in. According to Wan and Tsai [7], gust winds would have serious effects to the quad-copter in hover situation. In the work, we are more interesting in the tilted horizontal/vertical gust wind effects on the forward flight situation, to see whether the thrust coefficient might increase or decrease, depending on the wind direction and the rotor blades' RPM.

2.4 Heavy Rain Phenomenon

The earliest analysis of heavy rain effects on aerodynamic performance was done by Rhode [8], in that research he pointed out how the drag increase associated with the momentum imparted to a DC-3 aircraft under heavy rain cloud with "Liquid Water Content (LWC)" of 50 g/m^3 would cause a 18% decrease in the aircraft airspeed. The heaviest rainfall in history was recorded in Unionville, Maryland, during an intense thunderstorm on July 4, 1956, the rainfall rate achieved 1874 *mm/h* and it was recorded only for a period of approximately 1 minute, but usually the ground level rainfall rate would be much lower than that extreme value. What influence aircraft performance the most is the instantaneous rainfall rate but not the total rainfall amount, and the first author of this paper has done numerous simulation of heavy rain effects on the detrimental aerodynamic effects for different flight vehicles such as finite wing, wing with high lift devices, blended-wing-body configuration, helicopter rotor, etc. In this work we will further include the heavy rain physics and their simulation techniques into our quad-copter performance analysis.

2.5 Free-fall Situations

In "Task Force Recommendations Final Report" [2] several different assumptions are made; although it is not totally correct, but still it's worth to include as an important reference. From that report the assumption they made on the small free-fall quad-copter were the drag coefficient is about 0.3, the projection area around 0.02 m^2, and air density at sea level is 1.225 kg/m^3. From these assumptions they found that if falling from a 500 *ft* height, then different quad-copter weight will cause different degree of detrimental damage to ground personnel and some of the quad-copter did not even reach their terminal velocity yet. The other report "FAA UAS Center of Excellence Task A4: UAS Ground Collision Severity Evaluation Revision 2" [3] has more detailed descriptions than the previous one. In this report, it not only discusses about different quad-copter weight influence, but also examines the effects from different impact points and different impact angle when quad-copter fell. The most interesting part is that they have also made investigation on human bone's density and focus on the kinetic energy part of that impact. Thus arose our attention to find the correct free-fall terminal velocity and the aerodynamic performance coefficients for a typical quad-copter under different adverse scenarios.

3. Numerical Modeling

3.1 Numerical Flow Solver Setup

The size of our single propeller computational domain is 3600 in^2 for the cross section area and 250 *in* height, the disk is located at 50 *in* downstream from the entrance, and the geometry is shown in

Figure 4, with the diameter of the disk 11 *in* and 2 *in* thickness. The computational domain of the full-size quad-copter is 102400 in^2 for the cross-section area; the domain is made as a cube and is 320 *in* on each side. The rotor disk area is same as the single propeller case, 11 *in* diameter and 2 *in* thickness, their geometry is shown in Figure 5.

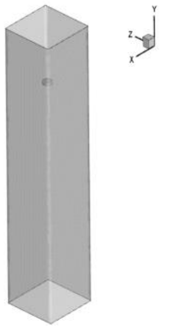

Figure 4 Computational domain of the single propeller disk.

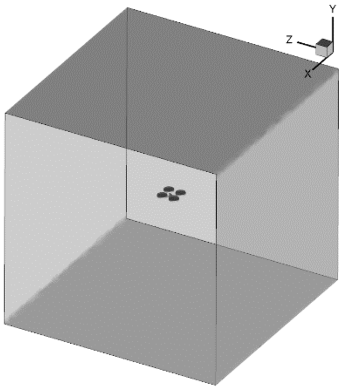

Figure 5 Computational domain of the full-size quad-copter.

The ANSYS Fluent solves conservation equations for mass and momentum [9], in this work the flow is incompressible so the energy conservation is not included. The equations of conservation of mass and momentum can be written as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \qquad (6)$$

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot (\overleftrightarrow{\tau}) + \rho \vec{g} + \vec{F} \qquad (7)$$

In Equation 7 the third term p is static pressure, the fourth term $(\overleftrightarrow{\tau})$ is stress tensor, the fifth term $\rho \vec{g}$ is the gravity force, and the last term $\vec{F}$ is external body force. Considering the propellers with constant rotating speed in this study, four rotating domains will be designated to simulate the rotational motion. The corresponding equations show the basis of multiple reference frame (MRF).

$$\vec{\omega} = \omega \vec{a} \qquad (8)$$

$$\vec{V_r} = \vec{V} - \vec{u_r} \qquad (9)$$

$$\vec{u_r} = \vec{V_t} + \vec{\omega} \times \vec{r} \qquad (10)$$

In the above equations, $\vec{V_r}$ is the relative velocity (the velocity viewed from the moving frame), $\vec{V}$ is the absolute velocity (the velocity viewed from the stationary frame), $\vec{u_r}$ is the velocity of the moving frame relative to the inertial reference frame, $\vec{V_t}$ is the translational frame velocity, and $\vec{\omega}$ is the angular velocity. It should be noted that both $\vec{\omega}$ and $\vec{V_t}$ can be functions of time.

Among the four segregated types of solver algorithms: SIMPLE, SIMPLEC, PISO, and Fractional Step FSM. Generally, PISO is better for transient cases, but when it puts the size of time steps into consideration, SIMPLEC would be a better choice in this study since PISO require more time steps. For turbulence modeling the SST k-ω (Shear-Stress Transport k-ω) had been chosen after extensive test that it gives better results for our validation cases compared with other turbulence models. On the other hand, although the hovering single propeller experimental data contains no freestream velocity, in current numerical simulation an extreme small freestream velocity is required. For all cases during hovering, a 1e-5 *m/s* freestream velocity is given and the three propeller rotating speeds are 2377, 4319, 6528 RPM, and the full-size quad-copter cases are same as single propeller cases that are given an extreme small freestream velocity. Table 1 is showing the numerical boundary condition setup of the single propeller and full-size quad-copter cases in our computation.

Table 1 Boundary conditions setup of singe propeller and full-size quad-copter.

Case	Single Propeller	Full-size Quad-copter
Body Surface	Symmetry	Symmetry
Rotor Disk Area	Interface	Interface
Side	Symmetry	Symmetry
Inlet	Velocity-inlet	Velocity-inlet
Outlet	Pressure-outlet	Pressure-outlet

3.2 Gust Wind Profile Simulation

A chaotic gust wind profile with 10 *m/s* mean speed is inputted and which roughly representing a Beaufort scale level 6 gust wind speed. The wind profiles could be further complicated to blow from different directions: forward, backward, leftward, rightward, upward, and downward, but due to the model of our quad-copter is symmetrical we only have to run the simulation in three directions, upward, downward, and rightward. Later the tilted direction cases are also included thus we will have a total five different directions of the relative wind, which is from 90˚ (upward or updraft), -90˚ (downward or downdraft), and 45˚/0˚/-45˚ (up-rightward, rightward and down-rightward respectively).

Then the simple freestream gust wind speed equation (5) could be further extended into a multiple functions realistic gust wind as shown below:

$$V(t) = 10(1 + 0.1sin(0.5t) + 0.1cos(0.25t) + 0.1\,sin(0.35t) + 0.1\,cos(t) + 0.1sin\,(0.1t)) \tag{11}$$

And this gust wind simulation profile is shown in Figure 6,

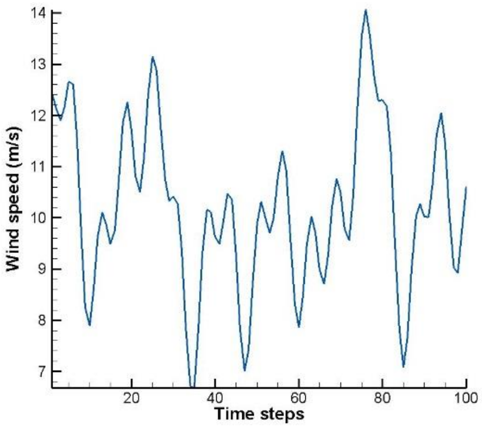

Figure 6 Gust wind simulation profile.

3.3 Heavy Rain Discrete Phase Model (DPM) Simulation

Heavy rain phenomenon has gained cloud physicist's attention for a long time, and obviously recent global warming and extreme weather's occurrence especially deserved more research efforts on it. Generally, there are three physical processes to produce rain droplets: condensation/deposition, coalescence and the ice crystal process. The heavy rain phenomenon we considered here is mainly due to the thunderstorm storm rain cloud which happened mostly in spring or summer months. According to Willis and Tattelman [10], the *LWC* parameter can be rewritten in terms of rainfall rate as:

$$LWC = 0.062R^{0.913} \tag{12}$$

Also Ulbrich [11] has found that the rain droplet distribution is somewhat similar to the *Γ*-distribution, and it can be expressed as:

$$N(D) = N_G D^{\alpha_c} e^{-\Lambda D} \tag{13}$$

Thus *N(D)dD* represents concentration of raindrops having diameters in between *D* and *D+dD*, and *D* represent as the raindrop diameter (*cm*). N_G is the concentration parameter, and the empirical equation of N_G is shown below:

$$N_G = \frac{512.85(LWC)\times 10^{-6}}{{D_0}^4}\left[\frac{1}{D_0}\right]^{2.16} \tag{14}$$

The medium volume diameter D_0 is computed from *LWC* as:

$$D_0 = 0.157 LWC^{0.1681} \tag{15}$$

The parameters in the modified *Γ*-distribution are determined as:

$$\Lambda = \frac{5.5580}{D_0}$$

$$\alpha_c = 2.160$$

The number of all raindrops *ND* at specific rain rate then can be calculated as the modified *Γ*-distribution:

$$ND = \int_0^\infty N_G D^{\alpha_c} e^{-\Lambda D} dD \tag{16}$$

And we can choose a diameter to represent all sizes of raindrops. The volume averaged means the droplet diameter D_m *(cm)* is chosen as the momentous parameter and is shown as:

$$D_m = \frac{\int_0^\infty D^4 N(D) dD}{\int_0^\infty D^3 N(D) dD} \tag{17}$$

The terminal velocity of raindrop is the function of its droplet size and altitude, it was discovered by Markowiz [12] and shown as:

$$V_T = 9.58\left(1 - exp\left[-\frac{D_m(mm)^{1.147}}{1.77}\right]\right) \tag{18}$$

The physical phenomenon of our heavy rain simulation is based on the parameters such as raindrop distribution, terminal velocity and droplet size. The “Liquid Water Content (LWC)” we had chosen to input is 19 g/m^3 which represents a heavy rain rate of 550 *mm/h*, and it was simulated by the “Discrete Phase Model (DPM)” of software. Consider that our rotor blades are spinning at a relatively high RPM, it is found that the best boundary to fit in the rotor blade is to “reflect”, and for the quadcopter frame structure we choose the “wall-film” boundary condition. These boundary condition selection is mainly due to the consideration of two-phase flow physics, and all the numerical schemes and boundary conditions set up has to go through a vigorous validation process first.

4. Results and Discussion

4.1 Validation

Our validation is to compare present numerical results with the experimental rotor blade data from the benchmark case done by Brandt et al. [13]. As shown in Tables 2 and 3, when it comes to the medium rotating speed of 4319 RPM, all three turbulence models give us quite satisfactory results, especially the SST k-ω model. We can see that although both models’ results are precise but the SST k-ω is always better, the reason may due to different model constrain on their Y+ values. These tables also show the high 6528 RPM cases always tend to be more accurate, and from Figures 7 and 8 we can clearly see the difference in their blade tip velocities at these two RPM speeds.

Table 2 Single rotor simulation results at 4319 RPM.

RPM	Cells (Millions)	Cp	Turbulence Model	Deviation	Y+
4319	Experiment	0.0474			
4319	3.2	0.0504	$k-\varepsilon$	6.3%	1.14-21.4
4319	3.2	0.0486	$k-\omega$	2.5%	0.2-17.9
4319	3.2	0.0480	SST $k-\omega$	1.3%	0.09-17.9

Table 3 Single rotor simulation results at 6528 RPM.

RPM	Cells (Millions)	Cp	Turbulence Model	Deviation	Y+
6528	Experiment	0.0531			
6528	3.2	0.0536	$k-\varepsilon$	0.9%	0.9-23.6
6528	3.2	0.0528	SST $k-\omega$	0.4%	0.48-14.9
6528	7.0	0.0525	$k-\varepsilon$	-0.9%	0.8-19.2

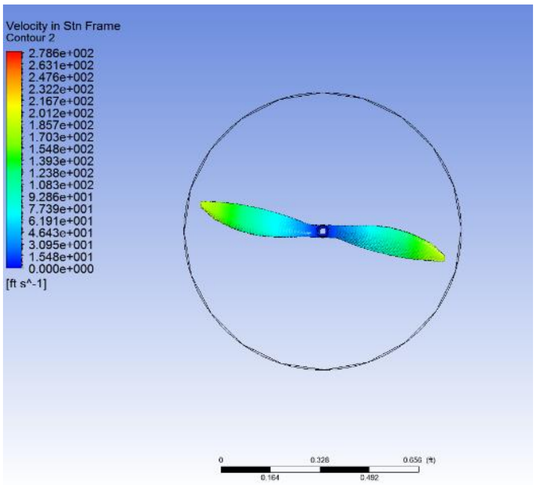

Figure 7 Propeller velocity contour at 4319 RPM.

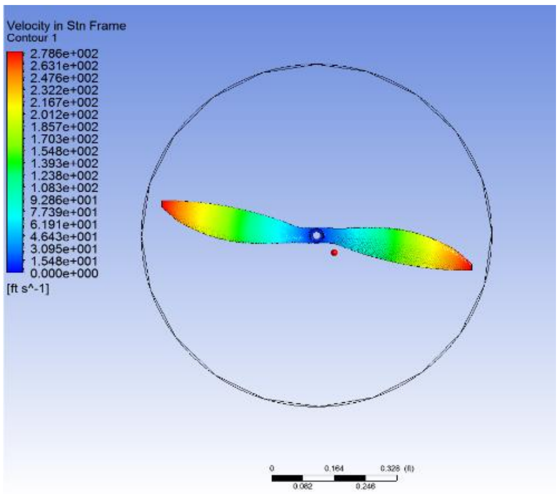

Figure 8 Propeller velocity contour at 6528 RPM.

4.2 Full-size Quad-copter Thrust Coefficient

For our case the reference area is the four rotor disk area (0.3424 m^2), and results will consult the experimental data achieved by Russell et al. [14] and the simulations by Yoon, et al. [15]. The full-size quad-copter thrust coefficient with different RPM and number of cells is shown in Table 4.

Table 4 Full-size quad-copter thrust coefficient with different RPM and number of cells.

RPM	Cells (Million)	C_T
4319	6.45	8.150e-03
4319	7.7	8.142e-03
4319	8.8	8.276e-03
6528	5.2	8.315e-03
6528	7.5	8.322e-03
6528	9.5	8.352e-03

To test the validity of our grid systems, this full-size quad-copter configuration is further computed with five different grids which ranging from 2.4 million to close to 20 million cells. The grid convergence results are shown in Figures 9 and 10, and it seems that again the higher 6528 RPM thrust coefficient is slightly converging better than the lower rotational speed case.

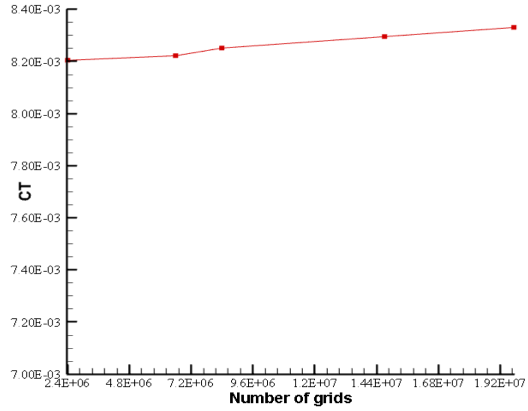

Figure 9 Grid convergence results for 4319 RPM case.

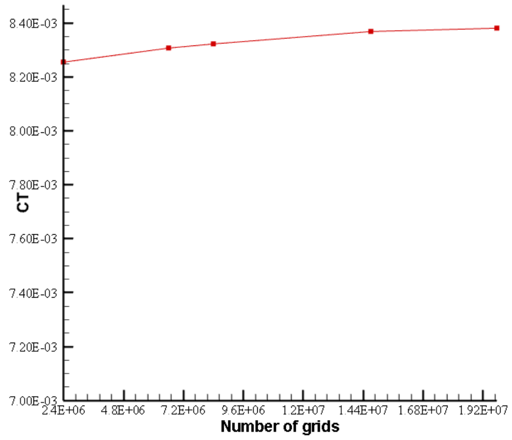

Figure 10 Grid convergence results for 6528 RPM case.

4.3 Free-fall Conditions

According to the Federal Aviation Administration (FAA) report [2], we can assume that if this quad-copter mass is about 1.4 *kg*, and when falling into the free-fall condition the drag force is about 13.73 *N*. In this case, the drag coefficient is still from the equation $C_D = \frac{D}{\rho A(\Omega R)^2}$, similar to C_T except now *A* represents the smaller projection area during the free-fall situation. Although there are many different quad-copter attitudes during its free-fall, in this work we only simulate one extreme and most hazardous condition, that is when falling in 90˚ vertically down, this situation is shown in Figure 11.

Figure 11 Quad-copter free-fall collision (90˚ down). [3]

If the flight altitude is high enough to reach the terminal velocity, our 1.4 *kg* quad-copter free-fall simulations with different propeller RPMs could achieve their force equilibrium conditions (*Drag force*=*Weight*), as shown in Table 5. It is found that if the propellers do not rotate, its terminal velocity is about 29.3 *m/s* and a blunt body type drag coefficient of 0.69; during 4319 RPM the drag coefficient will decrease, and this will cause the terminal velocity to increase, which is 40.6 *m/s*. Finally, for the high propeller rotational case that is 6528 RPM, the drag coefficient keeps decreasing to 0.31, on the other hand its terminal velocity will increase to 42.7 *m/s*. In each case it is also observed that most of the drag force come from the pressure drag produced by the propeller blades and the body frame, and during higher RPM cases their terminal velocities will also increase, with increasing detrimental kinetic energy values.

Table 5 Free-fall simulation characteristics values for a 1.4 *kg* quad-copter at different RPM.

RPM	Terminal Velocity (*m/s*)	Drag Force (*N*)	C_D	Kinetic Energy (*J*)
0	29.3	13.722	0.69	600.943
4319	40.5	13.752	0.36	1148.175
6528	42.7	13.738	0.31	1276.303

Our result could be compare with the data from FAA's report [2], we could make the same assumptions but now consider the quad-copter is falling from 500 *ft* height. The different sized quad-copter free-fall conditions are for the no propeller rotation situation, as shown in Table 6. In this table the falling velocities near the ground are computed for different quad-copter sizes and masses, for instance if the cross-section area is about 0.09 m^2 then the mass is 2.0 *kg*. By observing whether it could reach its maximum terminal velocity or not in the table, it can be concluded that if flying a quad-copter in a severe weather condition is indispensable, then we should at least fly at lower altitude to ensure it would not reach its terminal velocity and thus could guarantee the safety of ground personnel or to reduce the probability of lethality or severe injury. Since every dynamic system will eventually fail, thus fly low and fly light is indeed the key for safe quad-copter operation regulation in urban environment.

Table 6 Different sized quad-copter free-fall conditions at 500 *ft*. height with no propeller rotation.

Mass (*g*)	Cross-section area (m^2)	Velocity (*m/s*)	Reach Terminal Velocity
250	0.02	25.6863	YES
500	0.03	29.3071	YES
1000	0.04	34.5474	NO
2000	0.09	33.2099	NO

4.4 Hover under Heavy Rain Condition

For quad-copter hovering under the heavy rain situation, we found that the propeller blades' boundary conditions could set-up as "reflect" and the airframe surface need to activated as "wall-film" boundary condition, and other set-up parameters for a LWC=19 g/m^3 heavy rain are shown in Table

7. Compare the thrust coefficients at different propeller RPM in a heavy rain and hover flight condition, their result can be found in Table 8. These quad-copter thrust performance degradation were successfully activated via the built-in two-phase flow DPM mechanism as mentioned in Section 3.3. It is clearly shown that when the propeller blade speed is 4319 RPM which is medium rotating speed, the thrust coefficient under this heavy rain will decrease to 8.000e-03, or about 2.6% decrease from the no rain situation. For the higher case of 6528 RPM rotating speed, our simulation shows that under this LWC=19 g/m^3 heavy rain the thrust coefficient will decrease about 1.6%, and this seems once again prove the relative rigidity or robustness of the higher RPM or higher rotational kinetic energy situation.

According to our simulation we could conclude that if we trying to fly a quad-copter in a heavy rain weather, the quad-copter would lose part of its thrust, even though it is not a massive amount compare with the original total thrust but we should still be aware. Thus the best way to fly in heavy rain is to enhance its rotating speed and to reduce the loss of total thrust.

Table 7 Liquid Water Content (LWC=19 g/m^3) parameters set-up.

	Droplet Mean Diameter	Terminal Velocity	Droplet Distance
LWC=19 g/m^3	0.0028 *m*	8.06 *m/s*	0.0855 *m*

Table 8 Quad-copter thrust coefficient comparison for hovering under heavy rain and no rain conditions.

RPM	Conditions	C_T
4319	Without rain	8.217e-03
4319	With rain	8.000e-03
6528	Without rain	8.308e-03
6528	With rain	8.169e-03

4.5 Hover under Gust Wind Conditions

Next we engaged on the quad-copter hovering performance under a Beaufort scale level 6 gust wind condition with a mean speed of 10 m/s. All cases shown below in Tables 9 and 10 are the values we took average in between 0.4 *s* to 2 *s*, the purpose is to see the variation tendency of its thrust coefficient under different inflow direction gust wind which is vibrating and oscillating in nature.

Table 9 Quad-copter thrust coefficient comparison for hovering under different inflow direction gust wind at 4319 RPM.

RPM	Inflow Gust Direction	C_T
4319	No wind	8.221e-03
4319	-90˚	-2.579e-03
4319	-45˚	1.154e-03
4319	0˚	8.763e-03
4319	45˚	1.678e-02
4319	90˚	1.810e-02

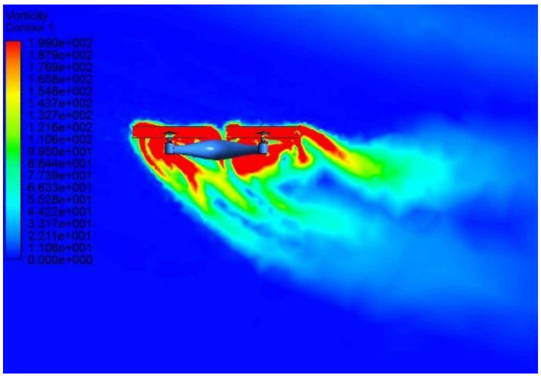

Figure 12 Quad-copter vorticity contour of gust wind direction from -45˚ tilted downward at 4319 RPM during hover.

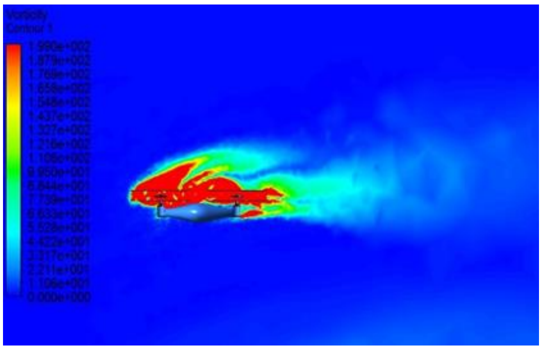

Figure 13 Quad-copter vorticity contour of gust wind direction from 45˚ tilted upward at 4319 RPM during hover.

At 4319 RPM and during hover, gust wind direction clearly has major impact on quad-copter's thrust level, as shown in Table 9. For gust wind came from side way which is 0˚ in our symbol, thrust coefficient increased to 8.763e-03 that is 6.6% more than the calm hover condition. For the other two downward directions, -45˚ tilted downward wind and -90˚ downdraft their thrust coefficient will decrease in huge amounts and with catastrophic or disastrous effects. On the other hand, it is clearly shown that for the 45˚ tilted upward inflow wind direction, its thrust coefficient will increase to 1.678e-02; for another wind direction, 90˚ updraft, the quad-copter will gain more thrust and thrust coefficient had substantial increased to 1.810e-02, both more than double its original thrust. Figures 12 and 13 are the quad-copter vorticity contour plots under the -45˚ tilted downward and 45˚ tilted upward gust wind situation, and their shedding vortices direction change is obviously observed.

Table 10 Quad-copter thrust coefficient comparison for hovering under different inflow direction gust wind at 6528 RPM.

RPM	Inflow Gust Direction	C_T
6528	No wind	8.306e-03
6528	-90˚	2.636e-03
6528	-45˚	3.884e-03
6528	0˚	8.796e-03
6528	45˚	1.155e-02
6528	90˚	1.181e-02

Carry on to the 6528 RPM cases, their tendency of thrust coefficient variation are somewhat similar to the 4319 RPM cases, but we can clearly see that the deviation between each cases do not have so much dramatic change as the 4319 RPM cases, either in enhance or degrade total thrusts. As shown in Table 10, from 0˚ direction the horizontal gust can help the quad-copter to enhance about 5.9% thrust coefficient, while same angle gust wind at 4319 RPM it can enhance 6.6% thrust. Other gust wind cases are -45˚ tilted downward, -90˚ downdraft, 45˚ tilted upward, and 90˚ updraft respective, compare with the calm situation which do not have any wind, their thrust coefficients were changing from 8.306e-03 to 3.884e-03, 2.636e-03, 1.155e-02, and 1.181e-02 respectively, representing a roughly 50% to 80% performance degradation or enhancement. Figure 14 is the q-criteria plot of 90˚ updraft at 6528 RPM during hover, while q-criterion is a parameter which can visual the overall 3-D vortices, and it is defined as the difference between the vorticity squared and the strain rate squared of the fluid element. It is observed that the 3-D vortices is mainly produced near the quad-copter rotor blade tips locations, and their asymmetric structure is mainly crated due to the gust wind profiles but not due to its wind direction.

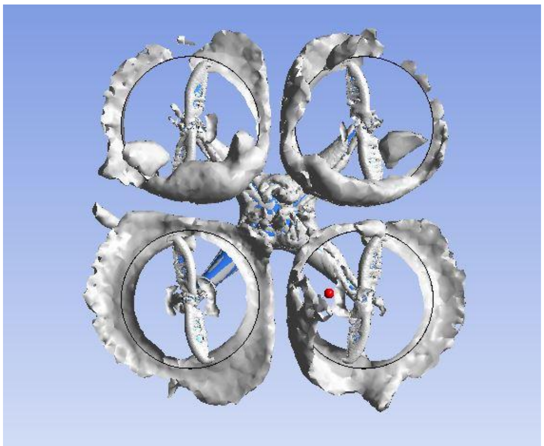

Figure 14 Quad-copter q-criterion of gust wind direction from 90˚ updraft at 6528 RPM during hover.

4.6 Forward Flight under Gust Wind Conditions

In this study, the quad-copter advance velocity is set as 10.7 *m/s* and the angle of attack, α, is -4.9˚. The reason for this particular angle of attack is because the fore rotors were set as 4319 RPM and the aft rotors were set as 6528 RPM. From earlier simulation we found that these four rotor blades at 6528 RPM can provide 44.402 *N* thrust, and if at 4319 RPM they can provide 19.223 *N* thrust. Then it is found that if this quad-copter has no angle of attack but with a forward velocity of 10.7 *m/s*, this simulation of thrust force could offset the drag force, which is 1.0763 N. Thus by the use of advance ratio and force balance equations we could come up with this -4.9 ˚ angle of attack value.

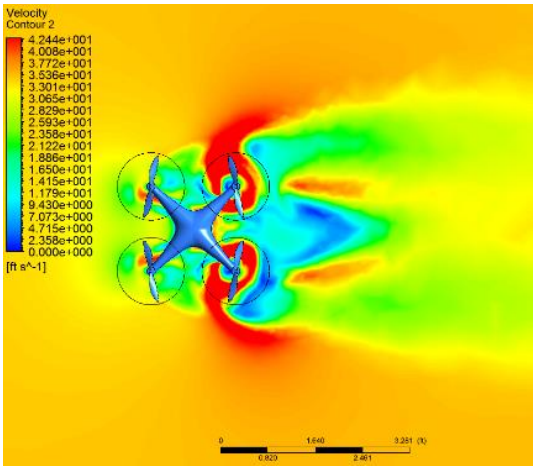

Figure 15 Quad-copter velocity contour with 10.7 *m/s* forward speed under gust wind.

Table 11 Quad-copter thrust coefficient comparison for forward flight under different inflow direction gust wind.

Forward Velocity	Inflow Gust Direction	C_T
10.7 m/s	No wind	8.710e-03
10.7 m/s	-90˚	-2.848e-02
10.7 m/s	-45˚	-4.069e-03
10.7 m/s	0˚	9.697e-03
10.7 m/s	45˚	2.785e-02
10.7 m/s	90˚	3.972e-02

Figure 15 is the quad-copter velocity contour with 10.7 *m/s* forward speed under the horizontal gust wind, and it seems compared well with other work. Also shown in Table 11 is the thrust coefficient comparison for forward flight under different inflow direction gust wind. It is demonstrated that at this moderate forward speed its thrust performance increase by about 5% if compared with the hovering case. For horizontal 0˚ direction gust wind its thrust coefficient will increase 11.3%, while the direction changes to -45˚ tilted downward the thrust coefficient will decrease to -4.069e-03, thus shows in forward flight, the gust wind will have more severe impact than the hovering condition. And for gust wind came from top, the 90˚ downdraft, thrust coefficient will decrease even more to -2.848e-02. For the -45˚ tilted downward and -90˚ downdraft cases, the quad-copter had lost all the thrust or lift to maintain its altitude. However, for gust wind came from 45˚ tilted upward and 90˚ updraft, it will help quad-copter to increase its thrust coefficient several times more which will also greatly upgrade its performance. These thrust coefficient severe change can also be observed from their vorticity contour plots when gust is blowing from different directions, as shown in Figures 16 and 17.

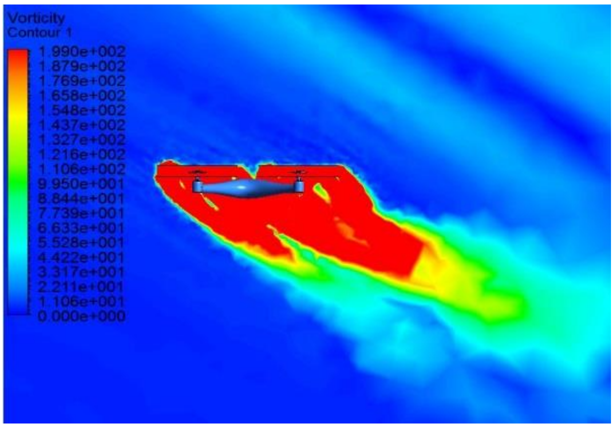

Figure 16 Quad-copter vorticity contour of gust wind direction from -45˚ tilted downward during forward flight.

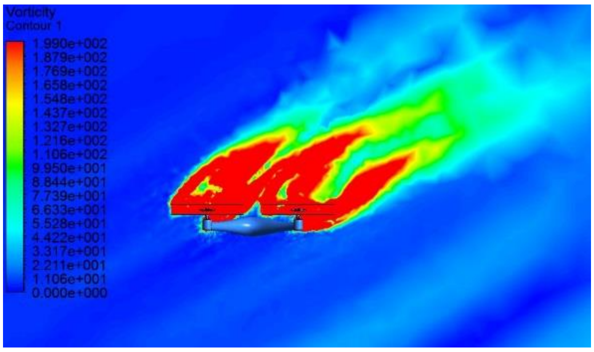

Figure 17 Quad-copter vorticity contour of quad-copter forward flight under gust wind direction from 45˚ tilted upward.

5. Conclusions

In this study the validation results seem quite satisfactory, it is found that the SST k-ω would be more suitable then other turbulence models for simulating flow field of quad-copter blade, and also the Y+ value has great impact on our simulations. If quad-copter is getting into a free-fall, their terminal velocity would be depending on both the flight altitude and its blades' rotating speed, if its altitude is high enough, higher blade RPM would cause a larger terminal velocity and thus might cause more damage on ground personnel. When encountering severe conditions that could cause quad-copter get into the free-fall condition, it is suggest that the operators should try everything possible to reduce the vehicle's altitude or slow down the rotor blades' speed and land on an open area.

If comparing the 4319 RPM and 6528 RPM under the heavy rain conditions, we could observe that flying at a higher rotating blade speed could reduce loss of quad-copter power and thrust. Similar results existed in the gust wind condition, higher RPM cases have fewer impact on the thrust coefficient, but if the gust wind inflow direction is coming from the upward or updraft directions, it would help to increase more thrust during the lower RPM situation. Our findings also reveal that if we want to maintain altitude and avoiding detrimental impact, quad-copter should fly at higher RPM. On the other hand, if we want to increase the flight altitude or save power when encounter gust wind, quad-copter should fly at lower RPM speed. Also the hovering and forward flight conditions will have different impacts if gust wind exists, and it is found that in forward flight, their impact would be much more severe.

In this study, it shows that if the operating quad-copter is under different severe weather conditions, their operators should use different techniques such as changing flight altitude or the rotor blade rotating speed, in order to reduce the possibility for accidents to occur. It is hoped that the research findings of quad-copter performance degradation under the gust wind or heavy rain situations could give more insight to both future UAV designers and operators, thus enhance future aviation safety standard and environment.

6. Contact Author Email Address

mailto: twan@mail.tku.edu.tw

7. Copyright Statement

References

[1] "DJI Official Website," https://store.dji.com/zh-tw/product/phantom-4-pro-v2?vid=43151.

[2] Unmanned Aircraft Systems (UAS) Registration Task Force (RTF) Aviation Rulemaking Committee (ARC) "Task Force Recommendations Final Report," Federal Aviation Administration, November 2015.Karbon, K.J., and Longman, S.E., "Automobile Exterior Water Flow Analysis Using CFD and Wind Tunnel Visualization," *SAE Technical Paper*, No. 980035, 1998.

[3] Arterburn, D., Ewing, M., Prabhu, R., Zhu, F., and Francis D., "FAA UAS Center of Excellence Task A4: UAS Ground Collision Severity Evaluation Revision 2," Federal Aviation Administration, April 2017.

[4] Silvestre, M. A. R., Morgado, J., and Páscoa, J. C., "JBLADE: a Propeller Design and Analysis Code," *International Powered Lift Conference*, Los Angeles, California, 12-14 August, 2013.

[5] Nguyen, D. H., Yu, L., and Koichi, M., "Aerodynamic Characteristics of Quadrotor Helicopter," *AIAA Flight Testing Conference*, Denver, Colorado, 5-9 June, 2017.

[6] Hairuniza, A. K. and Parvathy, R., "3D CFD Simulation and Experimental Validation of Small APC Slow Flyer Propeller Blade," *MDPI Journal of Aerospace*, Vol. 4, Issue 1, 2017.

[7] Wan, T. and Tsai, M. H., "An Investigation of Quad-rotor Aircraft Performance under Gust Wind and Heavy Rain Impacts," *AIAA SciTech Forum*, Orlando, Florida, 6-10 January, 2020.

[8] Rhode, R. V., "Some Effects of Rainfall on Flight of Airplanes and on Instrument Indications," NACA TN 903, April 1941.

[9] "ANSYS FLUENT theory guide," ANSYS Inc., November 2011.

[10] Willis, P. T. and Tattelman, P., "Drop-size Distributions Associates with Intense Rainfall," *Journal of Applied Meteorology*, Vol. 28, 1989, pp. 3-15.

[11] Ulbrich, C. W., "Natural Variations in the Analytical Form of the Raindrop Size Distribution," *Journal of Applied Meteorology*, Vol. 22, 1983, pp. 1764-1775.

[12] Markowitz, A. H., "Raindrop Size Distribution Expressions," *Journal of Applied Meteorology*, Vol. 15, 1976, pp. 1029-1031.

[13] Brandt, B. J., and Selig, M. S., "Propeller Performance Data at Low Reynolds Numbers," *49th AIAA Aerospace Sciences Meeting*, Orlando, Florida, 4-11 January, 2011.

[14] Russell, C., Jung, J., Willink, G., and Glasner, B., "Wind Tunnel and Hover Performance Test Results for Multicopter UAS Vehicles," *AHS 72nd Annual Forum*, West Palm Beach, Florida, 16-19 May, 2016.

[15] Yoon, S., Patricia, V. D., D. Douglas, B. Jr., Chan, W. C. and Theodore, C. R., "Computational Aerodynamic Modeling of Small Quadcopter Vehicles," *AHS Forum 73th Annual Forum*, Fort Worth, Texas, 9-11 May, 2017.