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Computational Fluid Dynamics Model Of A Quad-Rotor Helicopter For Dynamic Analysis

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Abstract

The control and performance of a quad-rotor helicopter UAV is greatly influenced by its aerodynamics, which in turn is affected by the interactions with features in its remote environment. This paper presents details of Computational Fluid Dynamics (CFD) simulation and analysis of a quad-rotor helicopter. It starts by presenting how SolidWorks software is used to develop a 3-D Computer Aided Design (CAD) model of the quad-rotor helicopter, then describes how CFD is used as a computer based mathematical modelling tool to simulate and analyze the effects of wind flow patterns on the performance and control of the quadrotor helicopter. For the purpose of developing a robust adaptive controller for the quad-rotor helicopter to withstand any environmental constraints, which is not within the scope of this paper; this work accurately models the quad-rotor static and dynamic characteristics from a limited number of time-accurate CFD simulations.

Keywords: CFD, control, disturbance, dynamics, quad-rotor, SolidWorks, UAV.

1. Introduction

CFD as a computer based mathematical modeling tool can be considered as the combination of theory and experimentation in fluid flows. It is now generally accepted and extensively used as a valid engineering tool in industry. Its computations are founded upon the fundamental governing equations of fluid dynamics – the conservation of mass, momentum and energy. These equations combine to form the Navier-Stokes equations, which are known to be a set of partial differential equations that cannot be solved analytically except in a limited number of cases. Nevertheless, approximate solutions can be obtained using discretization methods that approximate the partial differential equations by a set of algebraic equations. The most frequently used are the finite volume method, the finite element method and the finite difference method. The resulting algebraic equations relate to small sub-volumes within the flow, at a finite number of discrete locations.

Any air-breathing propulsion system, be it a pure jet, an engine-propeller combination, an engine-rotor combination, or a motor-rotor combination (like the quad-rotor helicopter), derives its net thrust by adding momentum to a volume of air [1]. Therefore, the production of thrust in helicopters is based solely on the action of the propeller. As the propeller rotates, it causes the air around it to accelerate from one side to the other, which results in the development of thrust in the opposite direction of the flow.

The aerodynamics of the helicopter is one of the most challenging problems facing aerodynamicists, but with the rapid increase in computational power and storage in recent times, CFD simulation has turned out to be a realistic way of predicting the air flow around the rotor blade. This certainly makes way for accurate prediction and understanding of the aerodynamics of the entire quad-rotor helicopter [2].

The physics which governs fluids is relatively simple; the laws of motion and thermodynamics with a little bit of chemistry. However, the solutions are very complex and this makes analytical methods largely unusable for industrial applications. A common engineering approach to such complex dilemmas is to replace the problem with a number of smaller less complex problems [3].

As the quad-rotor helicopter flies around, the fluid (air) in which it is submerged must move out of its way. The manner in which the air flows around it depends on its shape as the flow could be smooth but more likely will contain vortices, shockwaves and other disturbances.

This work presents details of CFD simulation and analysis of the quad-rotor helicopter. It starts by showing how SolidWorks software is used to develop a 3-D CAD model of a quad-rotor helicopter, with the same parameter values as that of the analytical dynamic model simulated in [4]. Computational Fluid Dynamics (CFD) as a computer based mathematical modeling tool is then used to simulate and analyze the effects of wind flow patterns on the performance and control of the quad-rotor helicopter.

2. Quad-rotor Helicopter CFD Studies

The flowchart in figure 1 shows the three major stages involved in using CFD to simulate a quad-rotor helicopter.

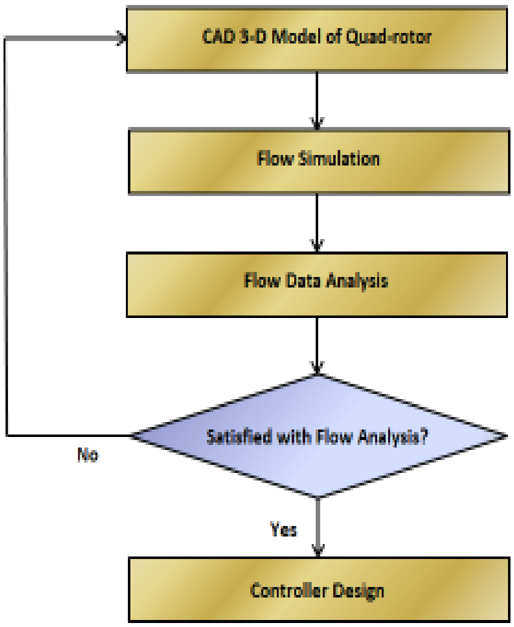


Fig. 1: CFD process chart

2.1 Computer Aided Design (CAD)

This involves making use of computer aided design software to build a model of the quad-rotor helicopter and to represent it in the flow domain. It entails the following:

- Approximation of the geometry – the geometry of the quad-rotor needs to be approximated by a geometric CAD type model. More accurate results are obtained from a model geometry that more closely represents the actual geometry.
- Creation of the numerical grid within the geometrical model – to identify the discrete, finite locations at which the variables are to be calculated, the geometry is divided into a finite number of cells that make up the numerical grid. Before doing this, it is necessary to identify the physical flow phenomena expected (turbulence, compressible flow, shocks, multiphase flow, mixing, etc.) so that the grid generated is suitable to capture these phenomena.
- Selection of models and modelling parameters – once the geometry and grid have been established, the mathematical models and parameters for those phenomena are then selected and boundary conditions defined throughout the computational domain.

2.2 CFD Flow Solver

This software tool simulates the quad-rotor helicopter's fluid environment using the grid for flow conditions as specified by the researcher. It involves:

- Calculation of the variable values – discretisation yields a large number of algebraic equations (one set for each cell). These equations are then generally solved using an iterative method, starting with a first guess value for all variables and completing a computational cycle. Error or residual values are computed from the discretised equations and the calculations repeated many times, reducing the residual values, until a sufficiently converged solution is judged to have been reached.
- Determination of a sufficiently converged solution – the final stage in the solution process is to determine when the solution has reached a sufficient level of convergence. When the sum of the residual values around the system becomes sufficiently small, the calculations are stopped and the solution is considered converged. A further check is that additional iterations produce negligible changes in the variable values.

2.3 Data Analysis, Presentation and Verification

It is important to analyse the flow data from the results of the flow-solver and continually modify the model until a design satisfaction is achieved. This involves:

- Post Processing – once a converged solution has been calculated, the results can be presented as numerical values or pictures, such as velocity vectors and contours of constant values (e.g. pressure or velocity).
- Solution Verification and Validation – once the solution process is complete, each solution should be verified and validated. If this cannot be completed successfully, re-simulation may be required, with different assumptions and / or improvements to the grid, models and boundary conditions used.

3. Quad-rotor 3-D CAD Model

Building such a model begins with a 2-D draft of the helicopter parts. The draft comprises of geometry such as points, lines, arcs, conics and etc. Measurements are then added to the draft to outline the size and positions of the geometry. The relationships between the parts such as their intersections at tangents, their being perpendicular or parallel or concentric are normally used to define attributes. With its parametric nature, SolidWorks allows the measurements and relations to drive the geometry. The measurements in the draft can be organized individually, or by relationships to parameters inside or outside of it [5].

3.1 Motors

The quad-rotor's actuation mechanisms are designed as shown in figure 2. Having designed one motor, it can be replicated to make up all the four motors required for the assembly. Each electric motor weighs about 40g, with the four of them contributing a 160g to the total mass of the quad-rotor 3-D CAD model.

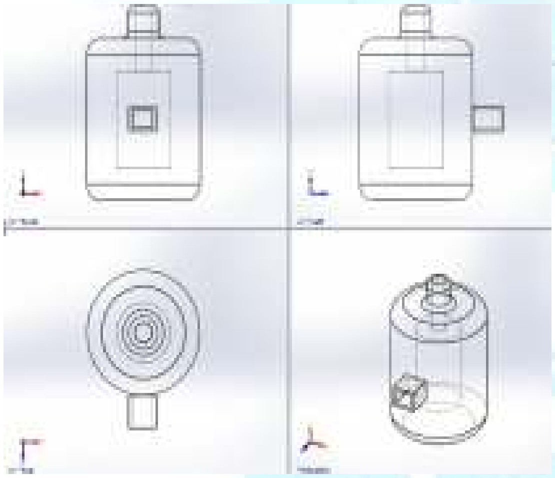


Fig. 2: CAD electric motor design

3.2 Arms

The quad-rotor arm normally made of light, but strong material shown in figure 3 forms a major part of the cross-frame. The length of the arm is measured from the center of mass of the quad-rotor helicopter to the end of the arm. There are four of them in this assembly, each weighing about 35g and having a motor mount (to which an electric motor is attached) at one end.

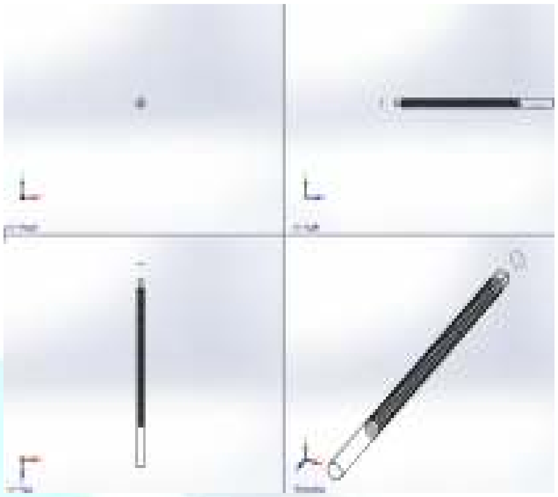


Fig. 3: CAD quad-rotor arm design

3.3 Propellers

The propeller blades are used to generate the aerodynamic thrust for lifting and maneuvering the quad-rotor. They have to be designed as airfoils with high aspect ratio in a shape that maximizes lift, yet minimizing drag from tip vortices as shown in figure 4. Each propeller weighs about 12.6g and is directly attached to a motor shaft.

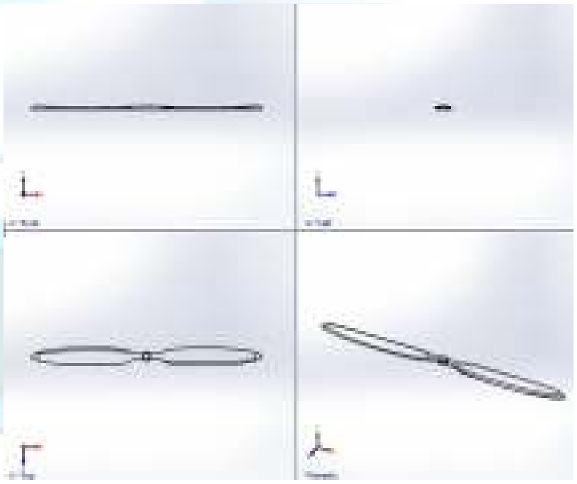


Fig. 4: CAD quad-rotor propeller design

3.4 Central Hub

The cross-frame (consisting of the four arms) passes through the center of the central hub, which houses the electronics in a flat bay area as shown in figure 5. Provisions can be made underneath the central hub for a payload such as camera or robotic arm, depending on the mission for which the quad-rotor is designed.

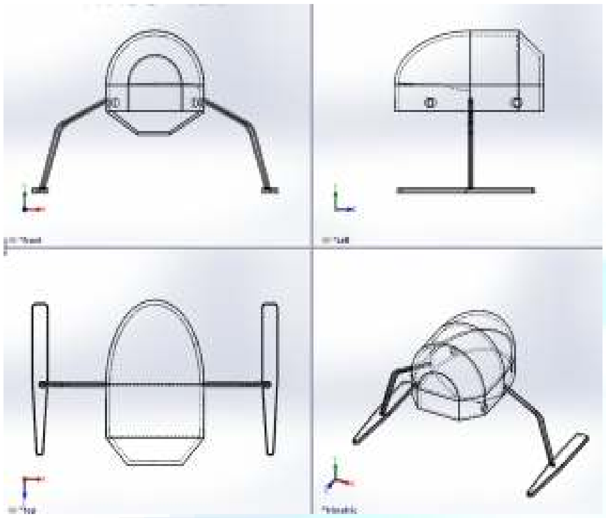


Fig. 5: CAD quad-rotor central hub design

3.5 Landing Gear

Quad-rotors could have different types of landing gears. However, it should be as light as possible, but strong enough to withstand any forceful landing as shown in figure 6.

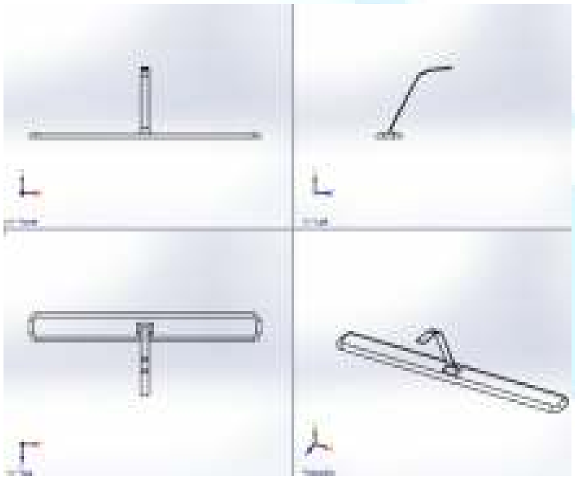


Fig. 6: CAD quad-rotor landing gear design

3.6 Payload

The camera payload is normally attached to the cross-frame, directly under the central hub. With it, the quad-rotor can do amazing stuff, when it comes to photography. A very light weight camera as shown in figure 7 has been included in this assembly.

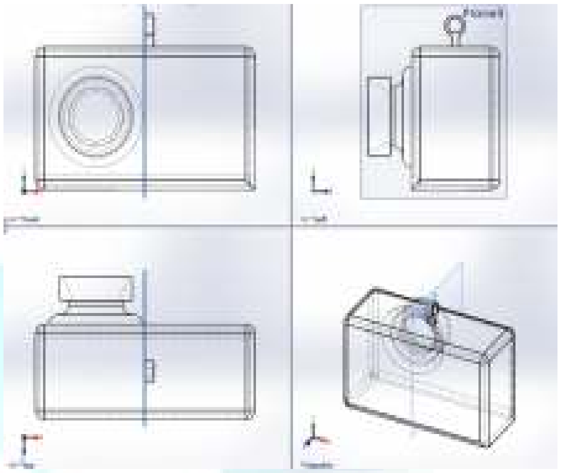


Fig. 7: CAD quad-rotor camera payload design

Once all the necessary parts of the quad-rotor have been designed, they fit together to finish up the quad-rotor 3-D CAD assembly as shown in figure 8.

Fig. 8: SolidWorks 3-D model of the quad-rotor helicopter

4. CFD Flow Simulation

The flow-solver used in this research work is SolidWorks Flow Simulation 2014, with its dialogue box shown in figure 9. Flow Simulation is a fluid flow and heat transfer analysis software fully integrated into SolidWorks. It simulates the quad-rotor helicopter's 3-D prototype in its working fluid environment, thereby giving predictions of the effects of the fluid flow on the helicopter prototype and the helicopter's effects on the fluid flow around it.

The outstanding feature of Flow Simulation is its intuitively clear and comfortable interface including a pre-processor for defining the type of analysis, specifying data and boundary conditions for the calculation (with an Engineering Database on substance properties); co-processor for monitoring and controlling the computation process and checking the convergence where necessary; post-processor for visualizing the results obtained [6].

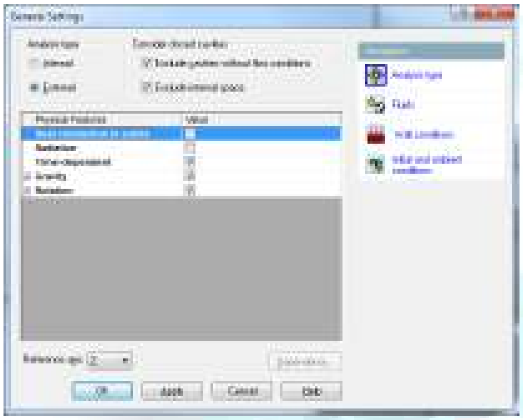
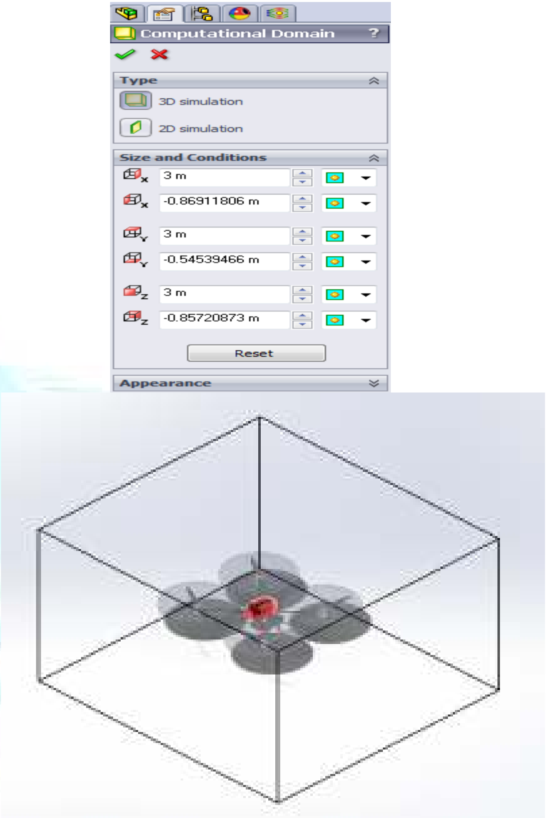


Fig. 6: Flow-solver dialogue box

The main objective of conducting the CFD simulation in this research is to simulate the effects of the external environment on the flow patterns of the quad-rotor helicopter within a given computational domain, which is normally a rectangular parallelepiped for both the 3D analysis and 2D analysis.

Its boundaries are parallel to the Global Coordinate System planes as shown in figure 10. Sometimes overlooked, the computational domain is one of the many important factors that influence the validity and accuracy of CFD simulation results. The use of different computational domains has turned out varied results, even for the same set of rotor speeds. Therefore, the choice of computational domain could significantly affect the results of such simulations.



X: 3 m
X: -0.86911806 m
Y: 3 m
Y: -0.54539466 m
Z: 3 m
Z: -0.85720873 m

Fig. 10: Computational domain of CFD simulation

In many cases, the advantage of working on a rectangular computational domain, with a uniform rectangular grid, compensatory to the more complicated form of the equation being used. The problem is finding the coordinate transformation, which maps the physical domain into the needed computational domain, such that the uniform rectangular grid in the computational domain corresponds to a non-uniform curvilinear grid in the physical domain [7].

Due to specified conditions, the characteristics of the fluid flow may have large variations in some regions in the physical space. In these regions, a refinement of the grid should be very useful, as it yields increased accuracy, without a supplementary computing effort.

The airflow is analyzed by starting from an initial flow, which can be either a guess at the solution or a specific initial condition. Using this initial flow the conservation equations are used to predict the flow a short time later. A new prediction is then made from the newly calculated flow. In this way the evolution of the airflow can be solved. In some situations (mostly when flying indoors or even outdoors without a disturbance), flows around the rotor blades of the helicopter are steady. For these steady flows, the process is repeated until the solution doesn’t change from one time to the next, i.e. a convergence. The opposite of this is when the flows around the rotor blades are unsteady. For these uneven flows, the solution never settles down and CFD aims to track how the flow changes with time [8].

Figure 11 shows the distribution of air around the rotors of the quad-rotor helicopter as they spin and add momentum to the volume of air they are immersed in. The lift force would normally rise perpendicularly to the air stream caused by Bernoulli Effect. This causes a lower pressure on top of the rotor blade, compared with the pressure at the bottom. The curvature on the top of the blade leads to a higher stream velocity than at the bottom and hence a lower pressure [9].

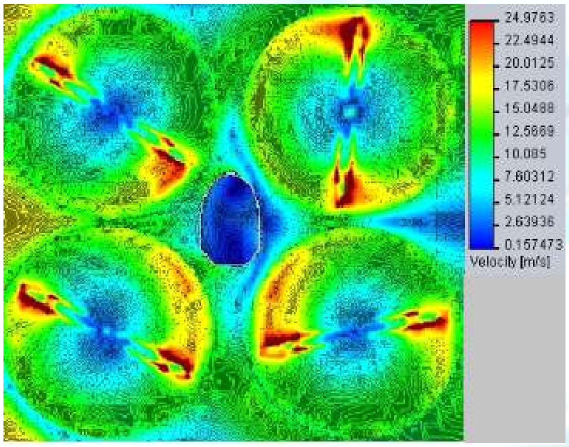


Fig. 11: Air distribution around the rotors during simulation

A close observation shows that near the ends of the rotating blades, there is some turbulence and the airflow tends to move upwards. Interactions between the wakes produced by the rotors and the fuselage, and also between individual rotors can also be observed. The cumulative air flow tends to go upwards, compensating the lift force.

5. Analysis of CFD Simulation Results

Wind speed and direction play important roles in flying any aircraft. The wind that flows opposite to the flight path of the quad-rotor helicopter (headwind) slams the front of the quad-rotor and slows it down, while a flow from the back (tailwind) forces the quad-rotor in the direction of flight, increasing its speed. There could also be crosswinds that blow from the sides, across the flight path and they are equally dangerous to the quad-rotor. These conditions can lead to loss of control or deviation from the flight path, depending on the magnitude of the winds.

Here, the quad-rotor helicopter experiences unsteady flows around its rotor blades, with winds speeds ranging from 0-15m/s in all the directions (x, y and z) as in figure 12.

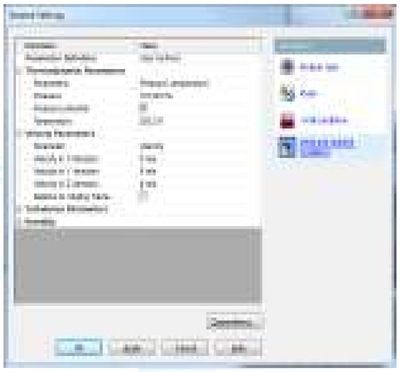


Fig. 12: Dialogue box showing how the different wind speeds were set

The helicopter rotors are working under different conditions, because of the varying wind speeds and the non-uniformity of the flow of air around them. This is expected to create some extra aerodynamic moments over the airframe.

With SolidWorks Flow Simulation, it is quite easy to calculate fluid forces and understand the impact of air flows on the performance and control of the quad-rotor helicopter as shown in figures 13 and 14 below.

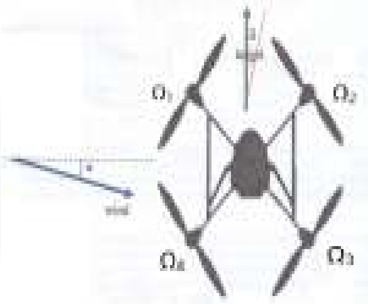


Fig. 13: Calculating the effect of wind disturbance on the quad-rotor helicopter

Based on the results obtained from the flow-solver, the effects of the vertical and horizontal wind flows on the quad-rotor helicopter are summarized and discussed next.

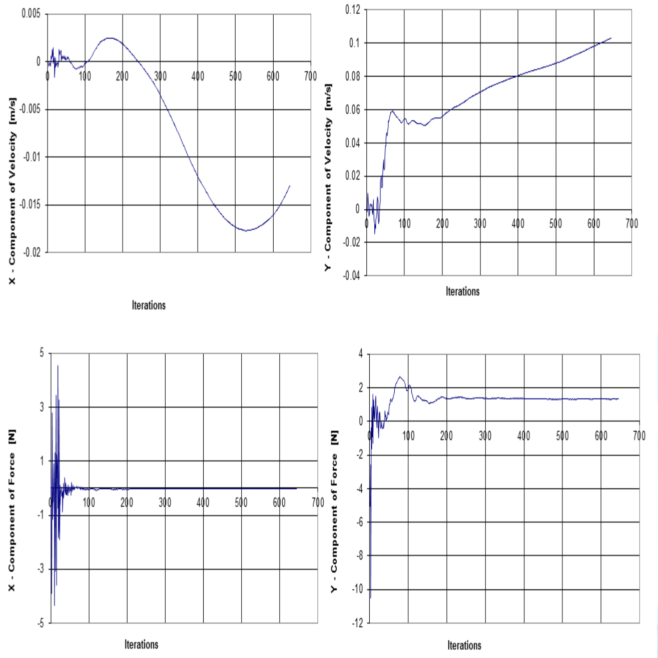


Fig. 14: Impact of air flows on the performance of the quad-rotor helicopter

5.1 Vertical Wind Flow

As the helicopter flies, it is normal to have airflows above and below it; the wind flow in the vertical direction could slam the helicopter from above or below and these would have different effects on the vehicle. In these simulations, the quad-rotor helicopter is allowed to experience both situations at different times and the results discussed.

At hover state, winds blowing at different speeds from the top of the helicopter will pass through the rotors from above and tend to decrease the thrust generated by the individual rotors, thereby causing a loss in the collective vertical thrust. This will force the quad-rotor to descend, unless the speed of the wind is reduced. With approximately the same wind speed (though with non-uniform flow) and higher angular velocities of the four rotors, the quad-rotor is able to oppose the force exerted on it by the wind and maintain its altitude, but as the force exerted by the wind overcomes the collective thrust generated by the rotors, the helicopter is always forced to descend.

The curves in figure 15 show a continuous reduction in the collective vertical thrust as the wind speed increases without a corresponding change in the motor speeds.

Since the air flow and distribution is not uniform, there is a possibility that the quad-rotor will either pitch or roll and move horizontally, even when a vertical movement is expected.

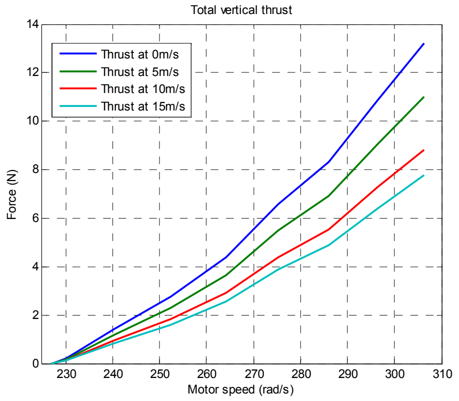


Fig. 15: Total vertical thrust in downward flow of wind

The exact opposite would happen if the wind blew from below the helicopter as shown in figure 16 below. The air will pass through the rotor blades from below and tend to increase the collective vertical thrust generated by the rotors, leading to the quad-rotor ascending to a certain height, only to stabilize when the wind or rotor speeds are reduced.

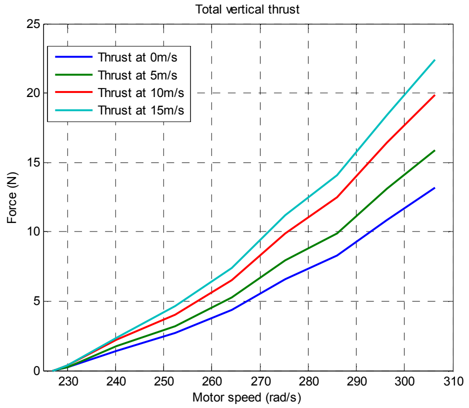


Fig. 16: Total vertical thrust in upward flow of wind

5.2 Horizontal Wind Flow

The horizontal wind velocity normally has a crosswind component and a headwind/tailwind component, which affect its speed relative to the ground. When the quad-rotor helicopter experiences such a flow of wind around it, there certainly will be unwanted moments in addition to other possible effects that act due to the fact that the flight conditions are much more unstable. The quad-rotor helicopter is likely to depart from the state of equilibrium in flight, leading to a possible loss of control.

Here, the quad-rotor helicopter was exposed to headwinds, tailwinds and crosswinds as depicted in figure 17.

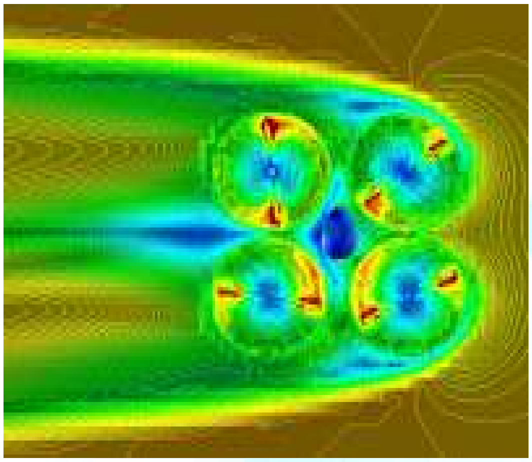


Fig. 17: Quad-rotor experiencing a cross wind in simulation

- Headwind

In a headwind situation, the effect of the wind slamming the front of the quad-rotor helicopter is seen from the curves in figures 18. The combined effect of the headwind and the helicopter's speed and forces always produces a resultant speed or force that is lower than the one the helicopter had before it encountered the wind. There could also be a change in direction of flight as suggested by the y-component (red line), depending on the direction and magnitude of the wind.

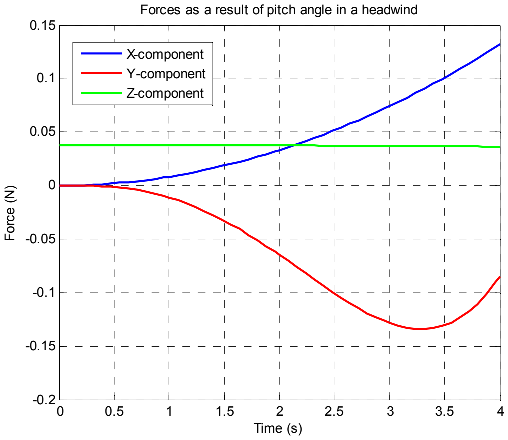


Fig. 18: Forces acting on the helicopter in a headwind

Stronger winds have a greater reduction effect on the quad-rotor's speed and forces as depicted in figure 19. Also notice that as the winds get stronger (red and light blue lines at 10m/s and 15m/s respectively), the quad-rotor seems to pitch violently as it struggles to stay in flight.

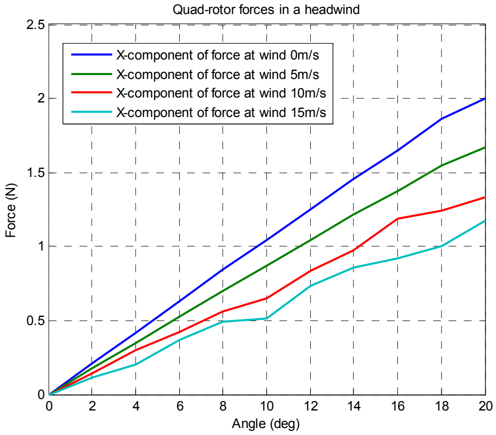


Fig. 19: Forces acting on the helicopter in a headwind at different tilt angles

- Tailwind

Naturally, a tailwind is expected to increase the quad-rotor speed and forces in the direction of flight as shown in figure 20 below. The effect of a tailwind on the forces acting on the quad-rotor helicopter may not be the exact opposite of the curves in figure 19 above as the effects of a headwind cannot be overcome by a tailwind of the same magnitude. Figure 20 shows increasing components of the x and y forces (blue and red lines) from 1-3 seconds of the simulation, while the z-component experiences a little decrease. However, after 3 seconds the y-component (red line) begins to decrease because of the fact that a tailwind would have a greater effect on the pitch angle/moments of the quad-rotor helicopter and also the non-uniform flow around it.

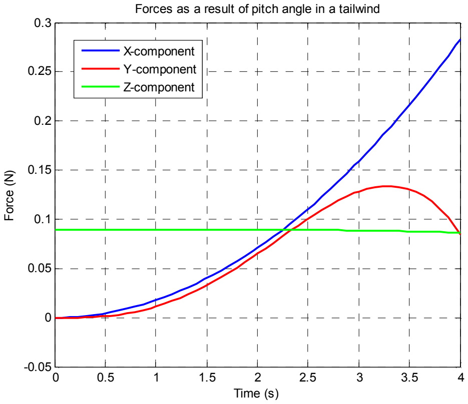


Fig. 20: Quad-rotor forces in a tailwind

- Crosswind

A crosswind would normally create an in-plane force that acts on the vehicle and tends to create a moment that makes the quad-rotor helicopter tilt. The instant the quad-rotor starts to tilt, it accelerates in its direction of tilt. However, too much of a tilt would make the quad-rotor to start loosing equilibrium, thereby leading to a possible oscillation and loss of control of the whole vehicle. Only a timely and accurate re-arrangement of the motor speeds can maintain that equilibrium and keep it in the planned path.

As shown in figure 21 below, the wind blows in the direction of tilt of the helicopter. The y-component (red line) of force increases with the crosswind, but since the flow is non-uniform, there is a fluctuation in the x-component (blue line) of force, while the z-component (green line) decreases. This clearly suggests instability in the vehicle because of the disturbance.

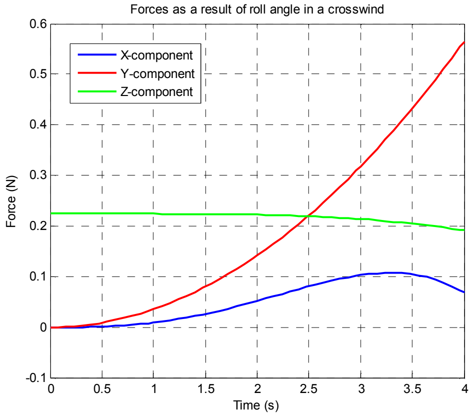


Fig. 21: Quad-rotor forces in a crosswind blowing in the direction of tilt of the helicopter

When the wind blows against the direction of tilt of the helicopter as shown in figure 22 below, the forces generally decrease. Notably, the x-component (blue line) of force reduces to the negative, implying that the helicopter moved in the negative x-direction. Such simulations would have been much easier if the winds hit the quad-rotor helicopter directly in front, at the back or from the sides. However, the curves clearly indicate the result of an uneven distribution of the force of the wind on the quad-rotor, making the problem of control even more complex.

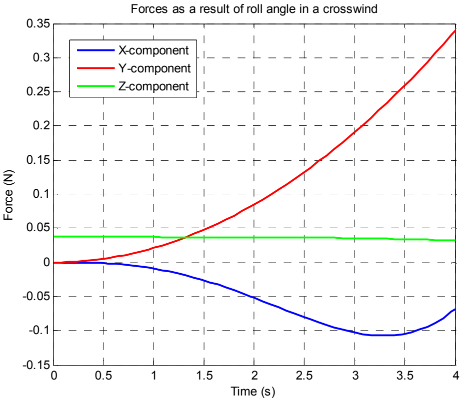


Fig. 22: Quad-rotor forces in a crosswind blowing against the direction of tilt of the helicopter

Figure 23 shows the major forces acting on the quad-rotor in a crosswind. An increase in the wind speed records an increase in the force if the wind is blowing in the direction of movement of the helicopter. Note that from 10m/s (red line), the force curve begins to oscillate, suggesting that the helicopter could be loosing equilibrium and possibly veering off the planned path. A further increase in the wind speed could even see the quad-rotor helicopter flip upside down and crash, if there is no adjustment made to the rotor speeds in good time. The direction of movement or behaviour of the quad-rotor helicopter can be difficult to predict if the wind is allowed to blow it off course.

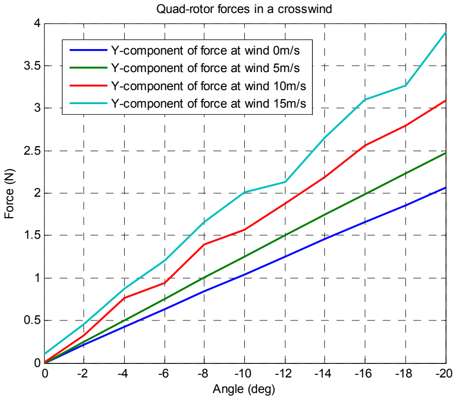


Fig. 23: Forces acting on the helicopter in a crosswind at different angles of tilt

6. Conclusions

CFD studies provide meaningful insight into the impact of fluid flow, enabling Engineers to address problems early, reduce the need for costly prototypes, and eliminate rework.

A 3-D SolidWorks model was also developed and CFD was used to simulate and analyze the effects of the external environment/disturbances on the flow patterns of the quad-rotor helicopter within a given computational domain.

The helicopter stability and control analysis requires a very large number of CFD simulations to determine appropriate forcing parameters within the expected range of motion. Typically, the time accurate CFD simulations start from a steady state solution and are iterated in pseudo time within each physical time step using a dual-time stepping scheme.

This work investigated the use of a 3-D SolidWorks model that significantly reduced the CFD simulation time required to create a full aerodynamics database, making it possible to accurately model the quad-rotor static and dynamic characteristics from a limited number of time-accurate CFD simulations, preparatory to the development of a robust adaptive controller for the helicopter.

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