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Framework for the Estimation of Safe Wake Separation Distance between Same-Track Multi-Rotor UAS

C.H. John Wang,^{*} Joshua Christian Nathanael,[†] and Ee Meng Ng,[‡]

Air Traffic Management Research Institute, Nanyang Technological University, Singapore 637460

Bing Feng Ng [§] and Kin Huat Low [¶]

School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798

As the surface traffic in modern cities becomes more congested, people turn to the vertical dimension to accommodate the projected increase in urban population density. In order to facilitate the utilization of the urban airspace for passenger and cargo transportation, however, a safe and efficient method of managing these traffic is needed. Several UAS (Unmanned Aircraft System) Traffic Management (UTM) concept of operations have been proposed and studied by various research agencies around the world to address this need, though hard data needed to validate the safety assessment of said concepts is lacking. The current paper proposes a hybrid Computational Fluid Dynamics (CFD)-Flight Dynamics simulation workflow to analyze the necessity of wake-vortex based separation standard for multi-rotor air-vehicles within the UTM controlled airspace. This is accomplished through the usage of Virtual Blade Model (VBM) to simplify the simulation of near-field wake of the multi-rotor air-vehicle, which is mapped into the LES domain to generate the wake-field that the SIMULINK flight dynamics model would use to generate the wake-encounter response of a follower multi-rotor air-vehicle. The outlined workflow could be used to estimate the attitude of the follower vehicle and the associate rate of change for a given encounter-pair at various separation distance, which could eventually contribute, along with other factors such as navigational uncertainties etc., to the establishment of required-sizing for safety “bubble” around an UAS. This safe-separation requirement would impact the safety assessment and the overall capacity of the UTM system.

I. Introduction

With the continuous increase in urban population and urban density and the associated traffic congestion, people have once again put their sight on the development of airborne passenger and cargo transportation within the urban airspace. Unlike the previous attempt with helicopter commuter services, the recent trend focused on the utilization of electric multi-rotor in the dense urban airspace. Regardless of the air vehicle setup, the future Urban Air Mobility (UAM) envisioned by many would involve a large number of air vehicle in an airspace confined by the various buildings and obstacles along the ground as well as the floor of the controlled airspace as the upper-bound. In order to facilitate UAS operations in the urban airspace, several UAS Traffic Management (UTM) concept of operations has been proposed in recent years to ensure its safe and efficient utilization, such as the SESAR U-Space, the NASA UTM, and the NTU/ATMRI TM-UAS.

Similar to the civil aviation traffic network, the strategic collision prevention and overall capacity of the UTM system depends on the separation minima requirement for the vehicles involved. The distance required to fulfill the separation minima depends on whether navigational error or wake-vortex encounter poses a bigger hazard to the following aircraft [1]. When applied to the UTM, the navigational based separation requirement would depend on the navigational aids available to the UAS [2], whether ground-based or vehicle-based. On the other hand, the hazard posed by the wake-vortex is based on its generation mechanism, the stability of the vortex pair, and the static and dynamic stability of the follower aircraft. The proposed workflow below aims to provide a way to estimate the hazard posed by a leader multi-rotor UAS on the follower UAS along the same track with various separation distances. The resulting

^{*}Research Fellow, AIAA Member

[†]Project Officer

[‡]Project Officer

[§]Assistant Professor, AIAA Member

[¶]Professor, AIAA Member, Corresponding author: mkhlow@ntu.edu.sg

wake-encounter stability analysis could then provide data to support whether a wake-vortex separation minima should be enforced under UTM. The problem could be broken down into three parts: the generation of near-field UAS wake, the evolution of the far-field UAS wake, and the wake-response of the follower UAS when subjected to the far-field wake at various following distance. The current paper focuses on modeling the wake-vortex encounter between a pair of identical recreational UAS due to the lower computational resources requirement and the availability of experimental data for validation.

II. Literature Review

While the wake-vortex field behind helicopters [3] has been studied for almost as long as that from the fixed-wing aircraft [4], the low density of helicopter traffic limited the number of studies on rotorcraft related wake encounters [5–7]. Observations from smoke-trail [8] and field measurements with LIDAR [6, 8–10] have shown that the wake generated by the helicopter when traveling at high speed (40 knots) behaves largely similar to the wake generated by a fixed wing aircraft; the wake generated by helicopter at lower speed is shown to be dominated by the downwash velocity and lacks a proper vortex structure. Similar observations were also made in the experimental and computational studies of wake generated by tilt-rotor at different mast-angles, with wake generated by near-vertical mast-angle being dominated by the down-wash [10–12]. As for wake generated by helicopters with multiple lift-generating propellers, i.e. multi-rotors, field-measurements suggested that the wake-vortex generated by the tandem-rotor CH-47 Chinook is weaker with 2/3 of the circulation comparing to a single-rotor helicopter of similar takeoff-weight and rotor diameter [8]. The same reduction in circulation was not seen in the side-by-side tilt-rotor V-22, which behaves like a conventional fixed wing at high speed when its masts are lowered to the horizontal position [10].

The computational simulation of the rotor-aerodynamics for helicopter is complicated by the dynamicity of the rotor controls in order to achieve stable lift generation, having to account for the rotor coning, flapping, and to an extent the aeroelasticity effect. To fully simulate the wake-vortex behind a rotorcraft, the solver would have to account for the change in the rotor collective and the resulting variable blade pitch as well as the fluid-structure interaction [13], though simplified models have been developed over the years that yielded acceptable results for specific flight conditions [7, 14–16]. The simplified model could be even more effective when modeling the wake of the modern electric air vehicles that uses fixed-pitch propellers with low aspect ratio, which minimized the influence by fluid-structure interaction; the multi-rotor urban air vehicles are also smaller and slower than the tandem/tilt-rotor helicopters, thus operates at a lower Reynolds number. For smaller multi-rotor UAS, the Reynolds number at which the vehicle is operating in is low enough that high fidelity transient simulations could be performed to obtain near-field wake given sufficient computational resources [17]. The smaller scale of the recreational UAS also means that detailed PIV measurements of the near-field wake could be taken for validation of the simulation results [18–20].

Data collection on the far-field wake-vortex behind a multi-rotor UAS is limited by the available instruments and test facilities. For example, the measurements of transport class aircraft’s wake-vortex using 2D LIDAR is mostly limited to ground effect region [21–24] with few research centers able to carry out airborne measurements [25]. Similarly, the availability of PIV measurements of mid to far-field wake-vortex with scaled-down fixed-wing aircraft model is limited by the required test-section length for wind-tunnel testing [26] and the availability of testing facility for water tow-tank testing [27]. However, given the lower Reynolds number regime that the recreational multi-rotor UAS operates in, it would be possible to perform full-scale transient Large Eddy Simulation (LES) to study the evolution of its far-field wake-vortex via the coupling of the near-field UAS wake, obtained either through full-propeller and UAS body simulations, simplified computational models, or experimental measurements. The coupling of the near-field and far-field domain could be through simple one-way mapping [28, 29], the detached eddy simulation, or two-way coupling of RANS and LES solutions [30], with the later two requiring specialized turbulence model and/or translation layer.

The wake-encounter response of a fixed-wing aircraft in a known wake-vortex field could be estimated by using the effective angle of attack to calculate the induced roll-moment, which could then be compared to the designed roll-authority of the aircraft for static encounter stability estimation [31, 32]. In comparison, helicopters with a single main rotor exhibit markedly different wake response, with the static (initial, uncontrolled) response to wake encounter dominated by pitching moment instead [33], the severity of the encounter, however, depends on the pilot/flight controller response and would need to include some form of control-loop modeling or human-in-the-loop simulation [33–35]. Studies done on the wake-encounter response of the UAS is even more rare with the majority of the studies focused on the fixed-wing UAS [36, 37], though some data exist on the wind-gust’s effect on the position-holding performance of multi-rotor UAS [38].

III. Simulation Strategies for Wake Encounter between Multi-Rotor UAS

The workflow and strategy for simulating wake-vortex encounter hazard between multi-rotor UAS is presented below: the first step is to simulate the near-field wake behind the multi-rotor UAS, which is dominated by the lift-generating surfaces; the next is to map the near-field wake to a larger domain to simulate the transient wake-vortex evolution; finally, the wake-response of a follower multi-rotor UAS is estimated at different following distance behind the leading UAS.

A. Near-Field Wake Simulation

While near-field wake simulation of the multi-rotor UAS exists with various level of flow resolution, the currently published data does not contain enough information to be used for solver validation [17, 19, 39]. In fact, the majority of near-field wake data for multi-rotor UAS are for the vehicle in hover conditions [18, 20, 40, 41], out of which the vertical velocity (downwash) profile from Ref. [18] and [41] were used for verification of the simpleFoam steady-state solver used in the current study; all validation tests were conducted under hover condition, i.e. $U_\infty = 0$. The results from Ref. [41] were chosen for part of the verification study due to the availability of the 3D-scanned propeller model used in earlier study on multi-rotor thrust [42], generously provided by Dr. Kutay of the Middle East Technical University. Additionally, the results from Ref. [18] were used to verify the swirl velocity and the resulting downwash-interaction in the simulation results.

Table 1 Mesh setups for the convergence study

Mesh Setup	Number of Cells	VBM Refinement*
Baseline	782,947	3
Coarse 1	433,506	3
Coarse 2	303,364	4
Fine 1	2,448,619	3
Fine 2	5,580,792	3

* Cell-region refinement level for snappyHexMesh utility.

Fig. 1 Downwash velocity contour plots sliced along the rotor axis for the mesh convergence study for simulation using VBM and K-Omega SST turbulence model.

Fig. 2 Rotor downwash using the VBM model setup with the “Fine 1” mesh at 3000 RPM with different turbulence models compared with the downwash-velocity contour from Ref. [41]

The downwash component of the near-field wake is modeled using the Virtual Blade Model (VBM), first implemented in OpenFOAM in Ref. [14]. Note that the default implementation of VBM in OpenFOAM is missing the inflow angle term (Eq. 3.53 from Ref. [43]), thus would under-predict the swirl velocity; the missing term has been added to the solver based on modifications outlined in Ref. [44]. An initial mesh convergence study, outlined in Table 1, and turbulence model study were conducted using the propeller blade profile extracted from Ref. [42] and compared to the CFD solutions and downwash velocity profile reported in Ref. [41].

The downward (negative y) velocity from the mesh convergence study showed little difference between the simulation results from different mesh refinement level, which is likely due to the way VBM maps the estimated downward velocity into the flow domain and the relatively low shear stress between the core and the free-stream (static) flow. This observation is apparent in the velocity profile plots (Fig. 3). The mesh refinement level could have more impact on the swirl-flow from the propeller, though no experimental data is available for verification purposes. On the other hand, the turbulence model study showed significant difference between the downwash velocity contours (Fig. 2), with the results from the Spalart-Allmaras turbulence model being the closest match to the results from Ref. [41]. The excessive dissipation of downwash flow with the other two turbulence models, the most apparent in the $k-\epsilon$ result, is likely due to the high shear stress between the core and the ambient flow due to the usage of simple cut-off type tip-factor.

The simulation setup was further compared to the downwash velocity profile reported in Ref. [45] as well as the PIV quiver/contour plots on inter-rotor wake interaction presented in Ref. [18]. Note there exist some discrepancy between the propellers pitch angels described in Ref. [45] and [18] even though the reported aerodynamics characteristics were identical*. This discrepancy with the propeller geometry could have contributed to the overall over-prediction of thrust from the VBM simulation as seen in Fig. 4; the simulation also did not account for the motor-stand from the experiment. Another possible source of difference is the simple tip-factor used in the model instead of the more complex Drela tip-corrector [44]. A comparison of the downwash-velocity contour is presented in Fig. 4 and 5. Note that the swirl-velocity vectors in Fig. 5(a) and Fig. 5(b) are not of the same scale.

B. Far-Field Wake Simulation

The far-field (outside of the body induced recirculation region, $> \sim 2$ vehicle length) wake simulations were conducted using the transient Large-Eddy Simulation (LES) turbulence modeling. This is due to the dynamic nature of wake-vortex evolution as well as the overly dissipative nature of the RANS turbulence modeling. For this simulation the near-field

*Ref. [45] reported a tip-pitch of 11.6° and $30\%R$ pitch of 28.1° , while Ref. [18] reported 10° and 20° . The VBM simulations were conducted using the first set of numbers.

Fig. 3 Downwash velocity profile plots at $Y = 1.0R$, where R is the rotor radius, for the (a) mesh convergence and (b) turbulence model study as compared with Ref. [41]

Fig. 4 Time-averaged downwash velocity contour from (a) PIV measurements from Ref. [18] and (b) the VBM simulation.

Fig. 5 Time-averaged downwash velocity contour at $Y = 0.2R$ from (a) PIV measurements from Ref. [18] and (b) the VBM simulation.

wake produced in Sec. III.A was mapped using the OpenFOAM mapField utility to the “inlet” of the LES domain in a similar way as the fixed-wing wake vortex simulation in Ref. [28]. The simulation was carried out in full-scale given the relative low Reynolds number of 3.22×10^5 based on vehicle length (0.5m), flight speed (10m/s), and the kinematic viscosity of the standard atmosphere ($1.55 \times 10^{-5} \text{m}^2/\text{s}$). The relative positions of the near-field mesh and the far-field mesh are shown in Fig. 6.

Fig. 6 The vertical sliced view of the $Z = 0$ m plane showing the near-field velocity contour (tilted square domain on the right) and the mesh used for the preliminary LES study (rectangular mesh on the left). The figure shows the scale of the far-field domain relative to the wake-generating (leader) UAS and the near-field domain. The LES domain is 10 m total in length and 5 m in height.

The turbulence model used for this study is the spatial dynamic-Smagorinsky sub-grid-scale model [46] implemented by Dr. Alberto Passalacqua [47]. Both the OpenFOAM LES solver pisoFoam and the implementation of the dynamic-Smagorinsky turbulence model have been extensively validated and used for the simulation of wake vortex for transportation-class aircraft [48–50], though mesh convergence study still needs to be done to validate the setup. Unlike the previous simulations, the current study focuses on the flow directly behind the wake-generating air vehicle (fixed distance relative to the vehicle) instead of a fixed domain (relative to the inertial frame of reference). For the preliminary test of the workflow, the LES domain was set to $\sim 40D$ in length, $\sim 10D$ in width, and $\sim 20D$ in height, where D is the single rotor-diameter (0.24 m in this case) of the UAS. The wake-generating multi-rotor vehicle was set to travel at 10 m/s with a pitch of -10° . The simulations were ran for 5s of simulated time to obtain the “standing” wake behind the aircraft, from which the velocity field of the wake-vortex could be extracted for the wake-response simulation. Note that the preliminary results were obtained with symmetry boundary at $Z = 0$ m to reduce the computational time and resources needed, thus the simulation was not able to capture the 3D wake-vortex interaction and would under-predict the dissipation due interactions between the induced secondary vortices. Note that the preliminary results were only generated to test the workflow with the encounter model and is not meant to simulate the actual wake-vortex generated by the multi-rotor UAS.

C. Wake-Response Simulation

The wake-response estimation of the follower UAS is described in this section. The method used is based on the simplified helicopter wake-encounter simulation described in Ref. [33], though the multi-rotor PID controller was used to model the “active” response to the initial attitude upset. The overall workflow for the one-way coupling of CFD generated UAS wake and the follower UAS response is shown in Fig. 7.

The impact of wake-vortex flow field on follower-UAS thrust production is estimated using the blade-element theory. Assuming that the rotor setup of the follower-UAS is identical to that described in Ref. [45], with a initial rotor RPM of 4890 and the PID loop of 250 Hz, the blade would sweep through 116.64° between each PID loops; the resulting forces at set sweep angles would be averaged to obtain the thrust and torque per rotor. The resulting changes in thrust and torque would be used to calculate the changes in UAS attitude and position, which is then feed into the PID controller to

Fig. 7 Flowchart of the wake-response estimation process for the follower UAS. The change in thrust for a given RPM due to wake-vortex is estimated using the blade-element theory.

obtain the response. The contribution of aerodynamics body-load is assumed to be minimal given the coverage of rotors over the main-body.

For this preliminary study, the UAS wake response simulation was conducted using the default multicopter attitude controller from the MATLAB™ SIMULINK example `px4demo_attitude_plant`, while the encounter-field was generated with a pair of extruded two-dimensional counter-rotating Lamb-Oseen vortices. The parameters for the pre-generated constant Lamb-Oseen wake-vortex pair and the parameters associated with the follower UAS that were changed from the default model are listed in Table 2. The follower UAS was placed at an offset from the centerline (at [0 0.5 0.1]) of the wake-vortex to induce an initial roll. The vehicle dimensions and the propeller parameters of the follower UAS was set to be the same as the leader (wake generating) UAS. Note that the body-drag calculation from the example file was retained, though the moment of inertia was increased by a factor of 10 to account for the change in mass.

IV. Preliminary Results of Workflow

A. Near-Field Wake Result

The near-field wake-vortex of a quad-rotor in forward flight was generated using the VBM with a symmetry plane along the longitudinal centerline of the UAS to reduce the computational time required. The quad-rotor was set with a forward tilt of 10° and traveling at a speed of 10 m/s, both numbers were obtained from Ref. [19]. The resulting near-field wake for the quad-rotor UAS is visualized using the $Q = 20$ iso-surface in Fig. 8. The value for the Q-criterion was chosen purely for ease of visualization.

Table 2 Wake Response Simulation Setup

Leader		Follower	
Variable	Values	Variable	Values
Γ_0 m ² /s	0.1	Mass (kg)	0.9
r_c (m)	0.02	Rotor Diameter (m)	0.25
b_0 (m)	0.8	Vehicle Diameter (m)	0.5

(a) Top View

(b) Side View

Fig. 8 $Q = 20$ iso-surface visualization of the near-field wake generated by a quad-rotor in 10 m/s forward flight with a forward tilt-angle of 10° . Note the soaring flow feature above the propeller plane in (b).

The simulation presented was only performed for the left-half of the quad-rotor, with the right-half mirrored along the $Z = 0$ m plane. One of the unexpected flow features that showed up is the soaring flow along the UAS centerline. This could be due to the constructive interaction of counter-rotating rotor-tip vortices along the centerline, thus creating a low pressure zone in the region. Since the UAS body/fuselage was not modeled in the current simulation, there is a possibility that the recirculation region behind the main body would have a sufficiently low pressure to counter this soaring flow. The soaring flow appears to be short-lived and dissipated after $\sim 2.5D$, while the fuselage-wake is assumed to behave similarly to that of the fixed-wing aircraft [28] and dissipate within a short distance behind the

vehicle. Future studies would need to look into the impact of the inclusion of UAS fuselage on the near-field wake generation and its ramification, if any, on the far-field wake evolution.

B. Far-Field Wake Result

Similarly, the simulation for the far-field wake-vortex evolution utilized the symmetry boundary condition to reduce the computational time for the preliminary study; mesh convergence studies were also not conducted for this proof-of-concept simulation. Due to the nature of the simulation, the resulting wake-vortex flow field should not be considered as realistic. However, the simulation results showed that the velocity field mapping utility was setup correctly and the boundary conditions did not create unexpected non-physical and/or numerical issues. The $Q = 20$ iso-surface visualization of the preliminary far-field wake is presented in Fig. 9, again with the right-half of the wake field mirrored from the solutions from the left-half.

(a) $t = 0.2s$

(b) $t = 5.0s$

Fig. 9 $Q = 20$ iso-surface visualization of the far-field wake generated by a quad-rotor in 10m/s forward flight with a forward tilt-angle of 10° . (a) is the earliest visualization available showing the near-field wake mapped into the LES simulation domain and (b) is the evolved wake vortex at 1 – 11m behind the leader UAS at $t = 5.0s$.

(a) UAS Positions

(b) UAS Attitude

(c) IMU Reported Attitude Change

(d) UAS Motor RPM

Fig. 10 Position, attitude, angular velocity, and motor RPM traces of the follower UAS from the wake-encounter simulation when subjected to a Lamb-Oseen vortex pair of $\Gamma = 0.1 \text{ m}^2/\text{s}$, $r_c = 0.02 \text{ m}$, and $b_0 = 0.8 \text{ m}$.

C. Wake-Response Modeling Result

The preliminary results from the wake-encounter model shown in this section was not conducted using the circulation measurements from the LES simulation, instead using the parameters listed in Table 2. This is in part due to the need to re-tool the circulation measurement subroutine for half-domain with symmetry plane along the centerline; the non-physical nature of the half-domain LES simulation served only as a proof-of-concept, while future works will be conducted with full-domain simulations. However, the simulation does show that the PID setup with the default parameters was stable when subjected to the static (non-descending) idealized Lamb-Oseen wake-vortex with a strength of $\Gamma = 0.1 \text{ m}^2/\text{s}$, resulting in a maximum induced-attitude change of ~ 0.042 rads before the vehicle departed the wake-vortex influenced region (Fig. 10).

In particular, Fig. 10(d) showed that the commanded motor RPM never reached the saturation point of 5000 RPM throughout the encounter. Note that the default PID controller from the PX4 demo does not include a derivative component, which could have some effect on the stabilization speed of the wake-response. A more detailed estimation of the moment of inertia for the follower UAS as well as the drag estimation could also contribute to a more realistic wake-encounter response.

Further simulations conducted with increasing circulation values showed that the follower UAS experienced a maximum roll angle of -0.19 rads when encountering a wake with $\Gamma_0 = 10 \text{ m}^2/\text{s}$ and completely flipped over when encountering a wake with $\Gamma_0 = 50 \text{ m}^2/\text{s}$, as seen in Fig. 11. Since the wake-vortex pair in the flow field was not descending, the follower vehicle would quickly depart from its initial flight corridor, which was under the influence of the wake-vortex, before stabilizing.

Fig. 11 Attitude of the follower UAS when subjected to very strong wake, notice that in (b) the UAS was flipped over at $t \sim 0.5$ s.

V. Discussions and Future Works

As discussed in Sec. IV, the preliminary simulation results were conducted using virtual blade model (VBM) with only half of the domain via symmetry boundary condition using the same multi-rotor vehicle dimensions and rotor parameters for the leader and the follower UAS. The VBM simulations of propellers in hover conditions were compared to existing data from the literature. The comparison suggested that while the downward component on the downwash is

similar to the data from literature, a more sophisticated rotor tip-model might be needed to better capture the swirl-flow gradient due to the tip effect. A smoother tip-model used with the VBM could also lead to better simulation results with $k-\omega$ SST and $k-\epsilon$ turbulence model. While the transient wake-vortex evolution using LES did not produce a realistic wake-interaction due to the symmetry boundary setup, it demonstrated that the boundary conditions and numerical schemes were set up correctly as well as the feasibility of the utility that maps the near-field wake into the far-field domain.

The wake-encounter model demonstrated that the PID tuning from the example file is sufficient to counter the idealized wake, though further refinement could be made to better account for the vehicle moment of inertia and drag coefficients. The obvious next step is to extend both the near-field and far-field wake simulation into the full domain, though some changes and more data gathering would be needed for the near-field simulation as well. Measurements from the far-field wake simulation could also be used to improve the encounter modeling, which could be done by either modifying the Lamb-Oseen model with measured characteristics or by direct importing of flow-field at set time intervals.

With the aforementioned improvements, it could be possible to model the wake-encounter response for a range of leader-follower UAS pairs. Given that the lift generated by rotorcraft in level flight is equal to its weight, the resulting wake should be proportional to the take-off wake of the UAS. The end-result from the encounter study could be similar to the weight categorization table for wake-separation in civil aviation. The exact maximum induced-attitude change and other stability or comfort related threshold would also need to be determined in future studies.

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