Understanding the downwash/outwash characteristics of eVTOL aircraft

CAP 2576

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Introduction

This paper presents an initial view of the effects of downwash for the safe operation of eVTOL air vehicles, reported fully in the main contractor report CAP 2576A. It does not constitute regulation and does not form a definitive view of the subject matter at this time.

The work is intended to provide a basis for further debate and discussion between manufacturers, operators and regulators. This should allow them to assess and, where needed, begin to address some of the issues found by this initial study of downwash in eVTOL operations.

The difference between our current knowledge on downwash, derived mainly from helicopters, and its impact on eVTOLs is the focus of the work. The potential risks and mitigations that result from any difference between helicopters and eVTOLs are presented, with a focus on the safety of passengers and personnel on the ground.

Next Steps

As noted in the main contractor report (CAP 2576A) the computational technique used has some limitations, such as its treatment of viscosity, the use of ‘perfect’ digital ground surfaces and the lack of wind. While these can be accounted and adjusted for by analysis they would need to be re-visited in light of any subsequent real-world verification and validation (V&V) testing that happens at full-scale.

The modelling in this work also has only a limited number of dynamic cases and vehicle orientations. As it is already clear that dynamic manoeuvres can significantly affect the downwash and outwash patterns it seems sensible to seek to expand on these at the earliest opportunity. It is especially recommended that this be undertaken in advance of any full-scale V&V work.

Wider engagement with manufacturers and potential operators of eVTOLs, and national aviation authorities, around the findings in CAP 2576A would benefit the work by opening its findings to challenge and identifying overlaps with other work that has been carried out globally.

A better understanding of limits and potential uses of a range of current computational methods for eVTOL design, testing and certification could help provide a clearer view of practical timelines for their safe use. This may be configuration-dependent.

An assessment of the effect of outwash velocities and the depth of outwash ground sheets and other phenomena revealed by this research on ground handling personnel, passengers on the ground, luggage and other items, ground equipment etc. would provide a better basis for understanding the overall impact of eVTOL downwash and outwash on safety.

Project Overview

Why we did it

The emergence of the electric Vertical Take-Off and Landing (eVTOL) sector has raised some novel technical and operational challenges. It has also revived some old ones. In the early 1960s the United States Marine Corps expected to replace helicopters with the latest innovation, tilt wing VTOL aircraft (Fig.A). However, research showed these could blow over equipment and people on the ground[1]. The Marines elected to stick with helicopters for the next three decades[2]. The reason was the aerodynamic phenomenon of downwash.

Figure A. XC-142 Tilt wing evaluated in the United States during the 1960s. Photo: NASA

Downwash is when the airflow used to support a vertical take-off and landing aircraft during powered-lift flight flows down towards, and interacts with, the ground. When this downwash meets the ground and turns outwards it is called outwash. Downwash and outwash have been experienced for many decades by helicopter operators (Fig. B). In helicopter operations they have caused fatalities as well as equipment losses and damage to infrastructure. The United Kingdom's Civil Aviation Authority (CAA) has sustained a programme of research into downwash in helicopter operations over a number of years. This has led to current best practice recommendations for helicopter downwash[3].

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[1] https://www.globalsecurity.org/military/systems/aircraft/c-142.htm accessed 11th September 2023

[2] https://sikorskyarchives.com/home/sikorsky-product-history/helicopter-innovation-era/sikorsky-s-65/

[3] See, for example, Civil Aviation Authority Publication 1264 (CAP 1264) Standards for Helicopter Landing Areas at Hospitals, 9 August 2019, available at https://publicapps.caa.co.uk/CAP1264, accessed 11th September 2023

Figure B. A Merlin helicopter’s downwash pattern revealed by sunlight illuminating water droplets. Photo: United Kingdom Ministry of Defence

In 2022 it was recognised by the CAA that eVTOL aircraft may differ from helicopters in two fundamental areas that affect downwash. Firstly, some eVTOLs have a higher ‘disc loading’ than a helicopter of an equivalent weight (Fig. C). Disc loading is the sum of the disc area of all of an air vehicle’s rotors divided by its weight. eVTOLs often use multiple rotors or propellors, instead of a typical helicopter’s single large one. The result is that for some designs their disc loading is greater that a helicopter of equivalent weight. Higher disc loadings usually mean higher downwash velocities.

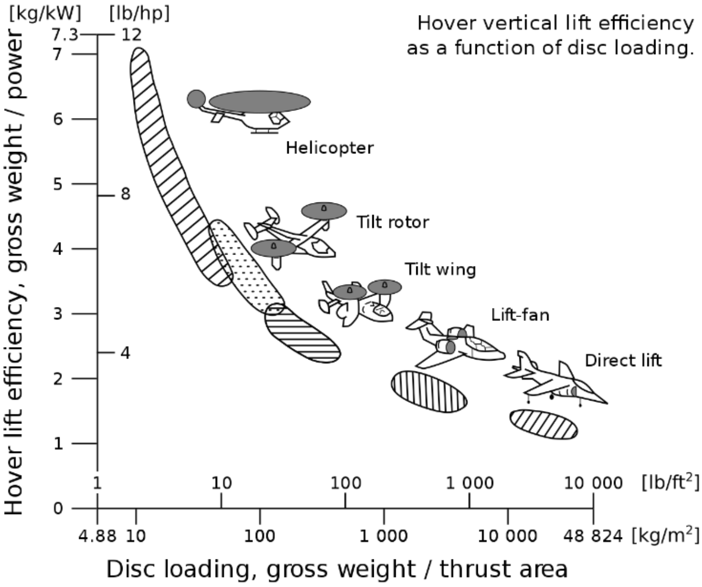

Figure C. Disc loading, weight and efficiency. Image: Newsom & Kirby (Ref. 30 in CAP 2576A)

The second area recognised in 2022 was that experience with military tilt rotors and ‘jump jets’ had shown that multiple jet flows from several propellors, rotors or jets produced a downwash pattern that differed from helicopters. Instead of a fairly symmetrical, circular pattern (Fig. D), the downwash from multiple flows could produce a more irregular shape. In particular, when several separate flow patterns interact they can produce ‘spikes’ that have a greater velocity than the overall average downwash or outwash airflow speed (Fig. E). With a helicopter, in general, the further away an observer on the ground is from the air vehicle the less the effect of its downwash. If eVTOLs experience ‘spikes’, however, it may mean that it is where the observer is located around the aircraft that may matter, not simply their distance from it.

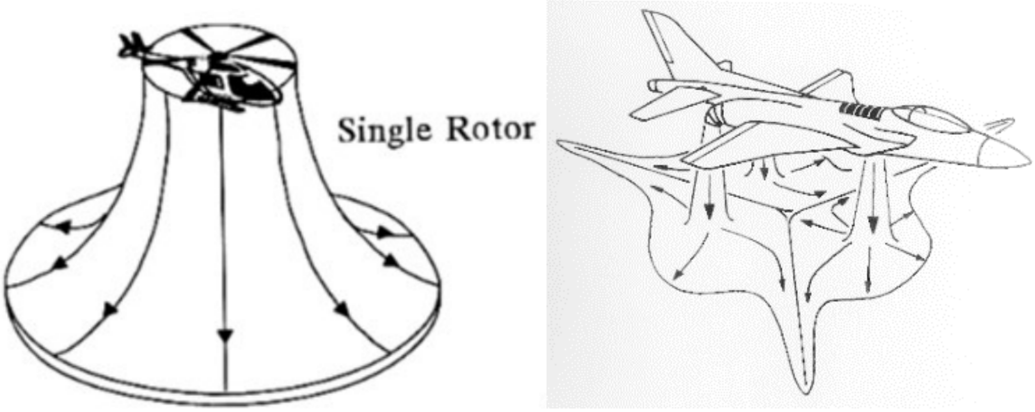

Figure D and Figure E. Single rotor helicopter circular downwash pattern on striking the ground compared to a notional jet-lift aircraft, showing how multiple jets combine to produce ‘spikes’ when their downwash hits the ground. Images: Ferguson (see Ref. 1 in CAP 2576A) & Cranfield University

Prior research in the military domain had shown these velocity spikes could double the speed of the airflow experienced by someone on the ground. In addition, where these spikes moved inwards and towards each other additional fountain flows could occur, where the downwash field reverses direction and rises back up to strike, and sometimes destabilise, the aircraft (Fig. F). Such fountain flows could, in theory, lift up material from the ground (Fig. G) and have been partly responsible for a number of tilt rotor incidents and accidents.

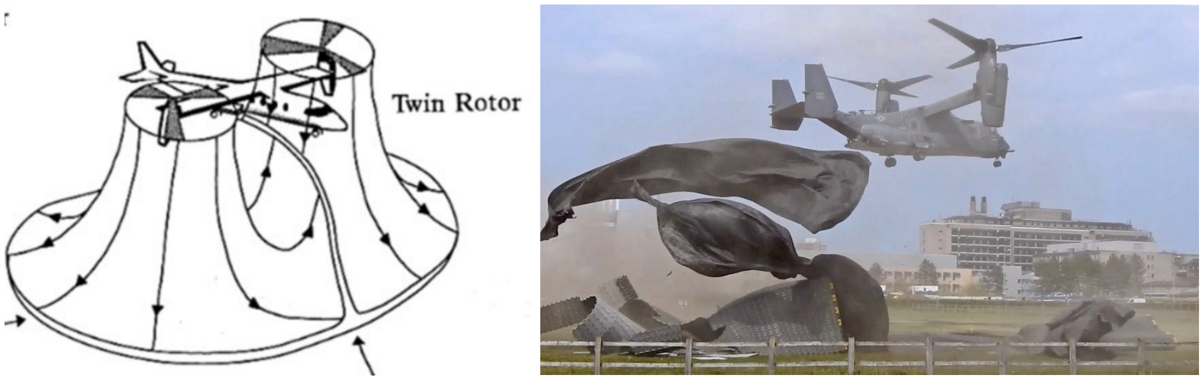

Figure F and Figure G. The downwash from a twin rotor producing an upwards fountain and a V-22 Osprey lifting the landing pad at Addenbrooke's Hospital, Cambridge, UK. The Osprey has a higher disc loading than a similar weight helicopter and experiences strong fountain flows. Images: Ferguson (see Ref. 1 in CAP 2576A) & YouTube

Neither of these issues are new. NASA has explored them for over half a century and they have been a standard part of VTOL aircraft design textbooks and courses for many decades. They have, until now, been largely confined to military aviation. CAP 2522[4], published by the CAA in March 2023, highlighted the potential impact of eVTOL downwash patterns, noting that further research would be required.

In mid-2022 the CAA made an informal approach to academics and industry professionals with extensive experience of modelling these phenomena. We sought to know if there was any work that filled the gap between military jet and tilt rotor experience and helicopter operations. It was confirmed that no significant work existed. It was within this knowledge gap that many eVTOLs were expected to operate.

In the autumn of 2022 this possible knowledge gap was given added urgency by a desire in the CAA to better understand eVTOL downwash in light of civil helicopter incidents. It is only by a sustained process of learning from experience, database building and theoretical understanding that existing helicopter regulation has progressed and it was to support this process for eVTOLs that the CAA undertook the research in this report. The intention was to see if any new, fundamental insights meant that existing legislation and regulation, based as it was largely around helicopter experience, was challenged by a better understanding of the specifics of eVTOL aircraft and downwash.

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[4] Future Flight Aircraft Capabilities: Exploring the requirements of next generation aircraft (CAP 2522), available at https://www.caa.co.uk/CAP2522 accessed 4th October 2023

What we did

The main focus for the study of eVTOL downwash by the CAA was assessing the effects of different propulsors or effectors (the collective term used for propellors, rotors and jets) on downwash patterns and intensity. This focus was driven by the knowledge of spikes experienced by jet lift aircraft such as the Harrier V/STOL fighter jet and the F-35B stealth fighter. This work is well illustrated by Kuhn, Margason and Curtis[5]. By exploring the significance of the location and size of propulsors or effectors on eVTOL downwash patterns it was hoped that the impact of specific configurational features could be captured.

The initial call for potential contractors left it open as to how these issues could be explored. The contractor chosen after competitive tendering elected to focus on a novel approach to computational fluid dynamics. As very many eVTOL configurations have been presented by companies around the world it was decided that the chosen contractor would be provided with a 'baseline' air vehicle layout that would allow a range of effector locations and types to be explored.

The baseline eVTOL concept designs were termed Air Mobility Platforms (AMPs) and were generated by the CAA. These are presented in Appendix A. 'Plain' basic layouts with wings and without wings were created. Using the work covered by Kuhn, Margason and Curtis it was thought that, as with much data analysis, an 'eyeball' estimate of possible intensified downwash and outwash could be added to the AMPs, shown by yellow arrows in Appendix A. A range of test cases were also generated for the contractor to apply to the AMP layouts.

The United Kingdom Defence Science and Technology Laboratory's (Dstl) air vehicle concept and rotorcraft specialists provided informal validation of the methods used to generate the AMP configurations. In addition, Dstl advised on the validity of the test cases suggested and added some further cases that they thought would matter.

The AMP configurations are propulsion agnostic (electric/hydrogen/turbine). The contractor created enhanced models of the AMP air vehicle concepts for use in their digital modelling tools. Regular meetings were held at which progress was monitored and initial findings presented. As part of this an initial literature review by the contractor helped to identify the test cases that offered the most value.

An overview of the work has been presented to a number of eVTOL and vertiport design, manufacturing and operating companies, and a mid-project overview was given to industry in June 2023 at a CAA eVTOL Safety Leadership Group meeting.

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[5] Kuhn, R.E., Margason, R.J., and Curtis, P., 'Jet Induced Effects – The Aerodynamics of Jet and Fan Powered V/STOL Aircraft in Hover and Transition,' Progress in Aeronautics and Astronautics Vol 217, American Institute of Aeronautics and Astronautics, 2006.

The findings of the contractor modelling, combined with their literature review, form the main part of this work and CAP 2576A gives a fuller view of how the work developed, and the rationale for the selection of a subset of AMP configurations and test cases to focus on as the work developed. The report has been peer reviewed by two internal CAA engineers, each with over thirty years' experience in helicopter safety assessment, including downwash. Externally it has been reviewed by the lead Dstl rotorcraft expert, Dr Richard Markiewicz, and by Peter Curtis of Aeralis, who has decades of experience in understanding V/STOL jet interactions. In particular his experience on the Harrier and F-35B programmes has been a key part of the background work this report draws on.

Additional supporting information has been provided by the United Kingdom Military Airworthiness Authority. The authors of this report extend their thanks to all those who freely gave their time to review the report. Any mistakes are solely those of the authors

What we found

The main report, CAP 2576A, has allowed the CAA to draw some initial observations on the effect of downwash and outwash on the safe operation of eVTOL aircraft.

A summary of these is shown below. One key point to note is the terminology used by the contractor shows that outwash is a better description of the main phenomena that affect eVTOL operations, rather than the more familiar one of downwash used for helicopter operations. As noted above on Page 5, when the downwash field meets the ground it turns outward to flow over the ground, hence the name outwash, and it is this horizontal flow along the ground that produces most of the effects of interest.

The current CAA observations of the analysis of outwash in this study are:

a. For ground handling personnel it may be important to be aware of the orientation of an eVTOL, especially at low level. It is also of note that it appears that the manoeuvres that most exacerbate outwash are the opposite of those for helicopters; for example with the nose pitched up a helicopter may 'roll out' a vortex, but with eVTOLs a wing rolled downwards may produce the same effect.

b. The current design of markings of helicopter Touch-down and Lift-off (TLOF) areas, Final Approach and Takeoff (FATO) areas and the Safety Area, as well as the use of size-based 'D Numbers', may not be suitable for use by some eVTOLs (Fig. H).

c. The modelling showed a fair similarity in the orientation of the most powerful outwash effects to the initial AMP 'eyeball' estimates. Along with the literature review undertaken this gives encouragement that some existing V/STOL aircraft knowledge (for example from tilt rotors and jet aircraft) can be applied to outwash problems raised by eVTOLs. This may make it easier for regulators and designers to assess possible outwash issues at an early stage.

d. Some computational techniques, such as the one used in this study, may offer significant assistance in advancing beyond ‘eyeball’ estimates in order to refine and assess a basic configuration, enabling optimisation of performance and safety.

e. The phenomena explored by the modelling provides a different starting point for understanding eVTOL downwash and outwash than the existing helicopter database, at least for the for ‘non-copter-like’ eVTOLs (i.e. those with wings and separated/asymmetric propulsors). The shape and intensity of the outwash field is driven by the separation and symmetry of the effectors used by eVTOL vehicles, by their their disc loading and probably by their weight.

f. Some of the visual representations of outwash used in this study may support a standardised way of showing full-scale test results.

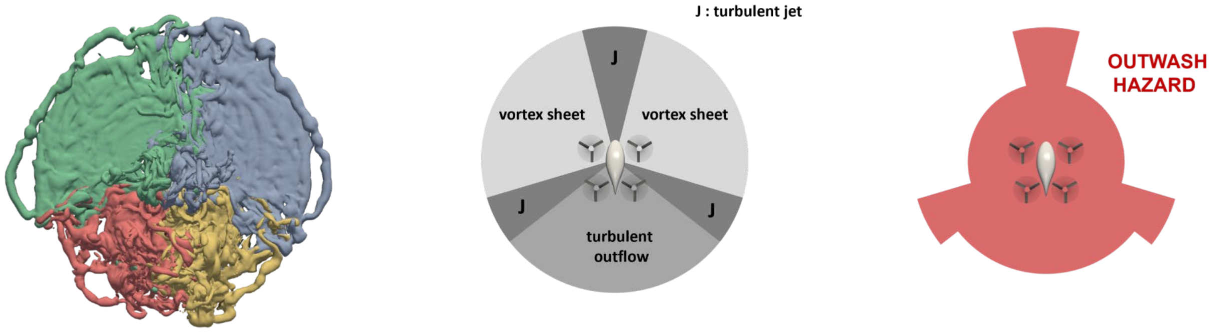


Figure H. Illustration from CAP 2576A of how complex flows can be reduced to possible hazard areas on the ground

Appendix A

The AMP Configurations and associated test cases used as a basis for the work in this report were developed by the CAA, with advisory support from Dstl Aerospace Systems Group. They provided a common basis for all air vehicle-based modelling carried out. This appendix outlines the material developed and provided to the contractor at the outset of the study[6]:

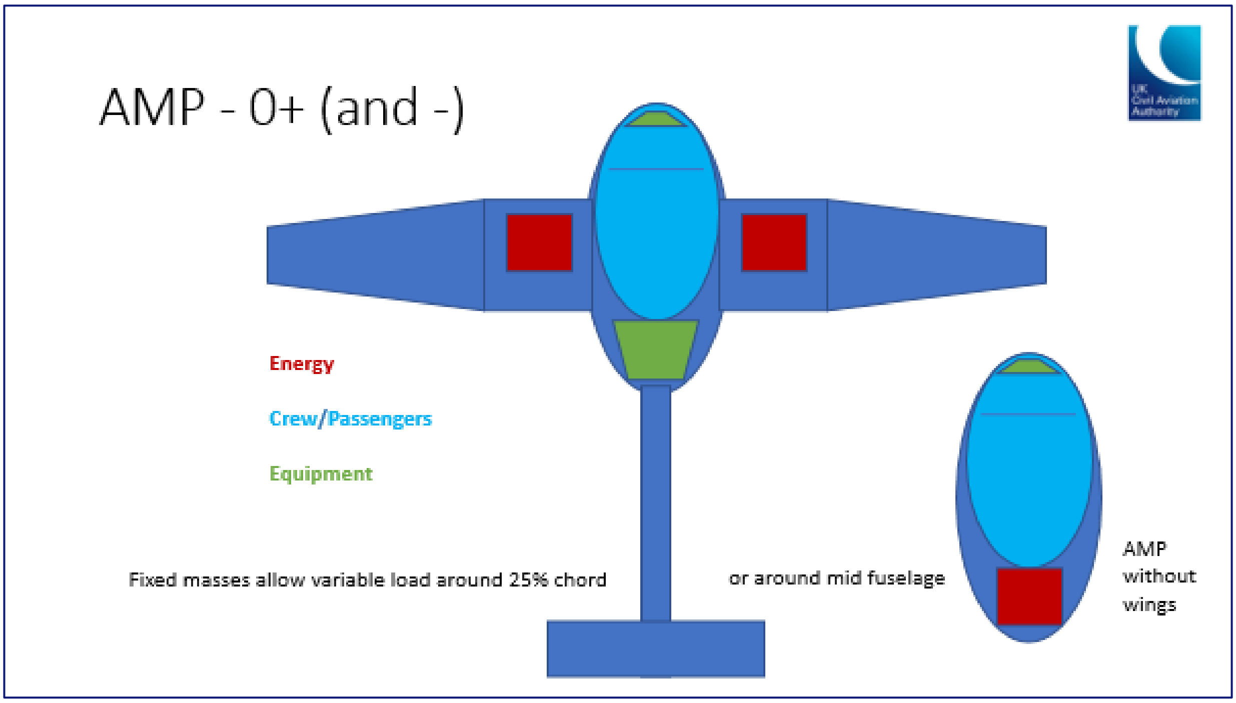
Overview

As part of a study into eVTOL downwash there was a need to assess the effects of different propulsion/lift effectors (i.e. prop, rotor, jet) on downwash patterns and intensity by exploring the significance of different effector locations, numbers and scales on a range of eVTOL configurations

As there are many hundreds of eVTOL configurations recorded[7] it was decided to generate a number of simple, generic eVTOL configurations, termed Air Mobility Platforms (AMPs)

The AMP configurations were used in contractor CFD modelling to allow a wide range of parameters to be studied from a common baseline. They are propulsion agnostic (electric/hydrogen/turbine) with lift 'effectors' that could be jets, rotors, propellors of fans.

Figure A1. Baseline AMP configurations (with and without wings).



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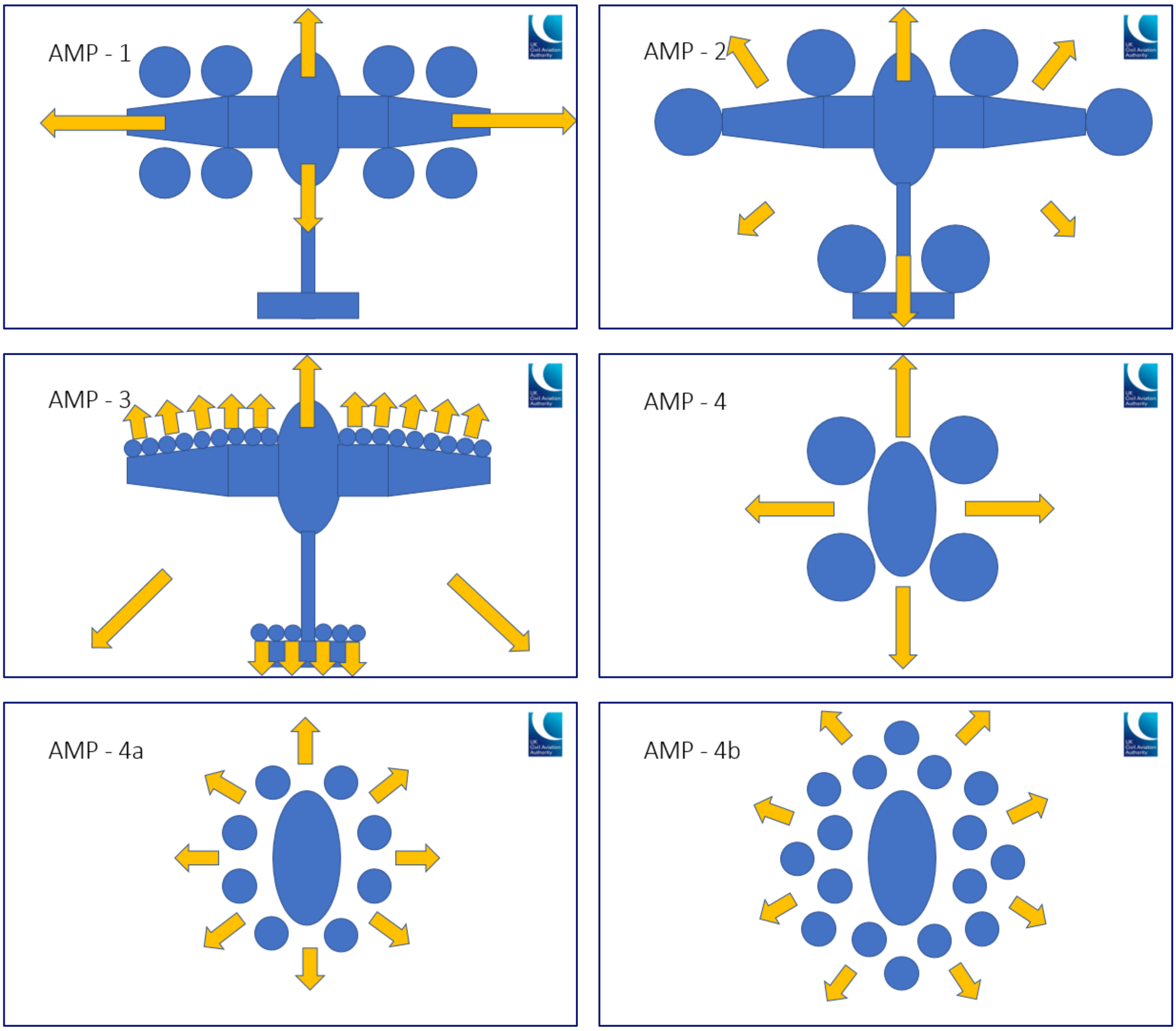
[6] Pryce, Michael; eVTOL Downwash Study Air Mobility Platform (AMP) Configurations, Draft 1.3; 14th Feb 2023

[7] See https://evtol.news/aircraft, accessed 11th September 2023

Figure A2. AMP configurations showing ‘eyeball’ estimates of potential outwash



Test cases and parameters

In discussion with Dstl a number of initial test cases and critical parameters were suggested as a basis for starting the modelling work. These were:

- Wing/effector position – High, Mid, Low, Tilt Wing
- No effectors or details of effector supports, motors, undercarriage etc. Added on case by case basis.
- Effector supports – in front/behind effector, detailed aero design
- Empennage – Vary for position (High/Mid) & thrust balance (wing 25% chord) twin/tri booms
- Effector plane – above/inline with wing/tail & top/mid fin & inclined plane
- Effector disc loading, swirl patterns, contra props etc.

- Effector numbers and positions - symmetry
- Failed effector/max moment demand (max thrust asymmetry), control effector ‘tilt’
- Gap between effector discs (ratio effector diameter/gap) – separation
- Control surface deflections – flaps/ailerons/elevators ‘down’ in hover (assume 25% of chord)?
- Undercarriage – min height used (undercarriage not drawn). Rolling VTO/VL?
- Test configs by contractor in number series (AMP-0abc/AMP-0123 etc.)
- Contractor config changes to be recorded as differences from baseline
- Static cases – Low/Medium/High weight range for each AMP config (scale factor?)
- Heights - effector plane/wing/vehicle (notional undercarriage) height
- Pitch/roll/wind angles (5/10/15… degrees)
- Steady wind (5/10/20… km/h)
- Then add dynamics – rates/gusts etc. Worst case (end of decelerating transition power levels)
- Standards – DSTAN 00-970 V/STOL cases & SC VTOL MoC criteria

In addition, a range of initial limitations and possible extensions to the modelling work were also proposed:

- First tests are hover/VL/VTO only – aero shape to ‘support’ effectors
- Effectors assumed to allow transition but not tested in first series
- Simple but realistic configurations may allow expansion to transition
- Comparison to helicopters in 750-3000kg range possible

As the active phase of the project developed the AMP configurations and the overall test programme were evolved in light of findings and limitations as shown in the main report, CAP 2576A.

Appendix B

Abbreviations used in CAP 2576 and CAP 2576A

- AMP – Air Mobility Platform
- CAA – Civil Aviation Authorithy
- CFD – Computational fluid dynamics
- DEP – Distributed electric propulstion
- DSTAN – Defence Standard
- Dstl – Defence Science and Technology Laboratory
- eVTOL – Electric vertical take-off and landing
- FAA – Federal Aviation Administration
- FATO – Final approach and take off
- NASA – National Aeronautics and Space Administration
- RANS – Reynolds Averaged Navier Stokes
- RMS – Root mean square
- SC VTOL – Special Condition VTOL
- TLOF – Touch-down and Lift-off
- UAV – Uncrewed air vehicle
- US – United States (of America)
- V/STOL – vertical and/or short take off and landing
- VL – Vertical landing
- VTO – Vertical take off
- VTOL – Vertical take-off and landing
- VTM – Vorticity Transport Model

Main Report – CAP 2576A

Sophrodyne Aerospace – Technical Report 10 October 2023

CAP 2576A
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1 Contents

2 Our principal findings

When a VTOL aircraft approaches the ground, the column of downwards-accelerated air that its propulsors create in the process of supporting the weight of the machine will be deflected outwards across the surface to form a fast-moving layer of air that spreads out in all directions below the vehicle, called its outwash.

Most of the aviation community's expectations regarding the likely effects of a VTOL aircraft's outwash on its surroundings currently derive from our experience with helicopters. There are strong reasons to believe that reliance solely on this experience may be insufficient when trying to understand the dangers that might be posed by the outwash that will be produced by the present generation of eVTOL aircraft when landing, taking off or manoeuvring near the ground.

Unlike helicopters, which generally have only one or two large, lifting rotors, a characteristic feature of all eVTOL aircraft is their use of multiple, small rotors in order to generate a combination of lifting and propulsive forces. These rotors are often arranged within a very compact footprint, causing the aerodynamic interactions between them to be particularly strong. This causes the aerodynamic behaviour of eVTOL aircraft in general to be markedly different to that of conventional helicopters. One of the consequences of these differences in aerodynamic behaviour is that eVTOL aircraft will produce a pattern of outwash on the ground, especially when in hover or in low-speed forward flight, that is very different to that which is produced by conventional helicopters.

As with helicopters, the prime factor that influences the strength of the outwash that is produced by an eVTOL aircraft is the disc loading of its rotors – in other words, how much weight is being carried per unit area of its propulsors. With very few exceptions, the eVTOL aircraft that are currently on the drawing boards or are entering the early stages of commercialisation have disc loadings that are significantly greater (in some extreme cases as much as four times higher) than those of conventional helicopters that have the same weight.

The argument as to whether this increase in downwash velocity will necessarily translate into an increase in *outwash* velocity when these aircraft interact with the ground needs to be approached with care. Many eVTOL aircraft, particularly the smaller, lighter ones, are indeed likely to produce a perfectly benign outwash. Our analysis suggests the existence of a particular area of concern within the design space, however, where the aircraft are heavy enough to produce an outwash that has considerable strength. Our analysis suggests that the velocities that are produced in parts of the outwash that is generated by this particular subset of eVTOL aircraft could be as much as two to three times those that are produced by conventional helicopters that have the same weight. Given what we know about the aerodynamics of eVTOL aircraft, it is possible that these vehicles might thus pose a distinct threat to personnel and infrastructure on the ground near to where these vehicles are operating.

A particular contributor to this problem is the fact that the aerodynamics of the interaction between multiple propulsors and the ground tends to cause the flow to concentrate along a few, relatively sharply-defined axes. The flow along these axes is jet-like: within these jets, the outwash velocities are locally much higher than elsewhere around the periphery of the vehicle. In addition, the flow within these jets is far more turbulent and unsteady than in the remainder of the outwash. The potential thus exists that the outflow along a few critical directions away from the aircraft may be damaging to an extent that is not encountered with more traditional rotorcraft (although the operators of somewhat more esoteric rotorcraft designs such as the Chinook tandem-rotor and the V-22 tilt-rotor will attest to the existence of similar effects in their outwash). The orientation of these jets remains fixed with respect to the aircraft, so as the vehicle manoeuvres near the ground there is a distinct danger that very sudden and unexpected upset be caused to nearby personnel and infrastructure as one or other of these jets sweeps past their location. Indications are that the unsteadiness of the flow within these jets may pose a particular risk to personnel on the ground, exposing them to sudden, unexpected buffets of wind that, even when experienced at quite low intensities, their physiology is not particularly well-suited to countering.

Not all eVTOL aircraft behave in the same way. An essential characteristic of the aerodynamics of this class of aircraft is that the pattern and strength of the outwash that any particular vehicle will produce is strongly influenced by the details of its design. The parameters that influence most directly the shape and strength of the outwash that a particular vehicle will produce are the size and number of the aircraft's propulsors, their location relative to each other and to other parts of the vehicle - such as the wings, fuselage and tail surfaces - and indeed the height of the propulsors above the ground. For this reason, different aircraft stand to exhibit markedly different outwash characteristics, meaning that individual vehicle designs may have to be treated on their own merits regarding the likely impact that the aircraft's outwash will have on its surroundings.

We also know that the operating conditions of the vehicle, as defined in terms of the thrust distribution between its various propulsors, the speed at which it is moving across the ground, and whether it is in steady or manoeuvring flight, will all influence the geometry and strength of the outwash that the vehicle will produce. Helicopters are known to produce intense, vortical, roller-like structures in their outwash which can propagate laterally outwards from the vehicle. These structures can extend out to considerable distances into the surrounding air when the vehicle is operated at certain combinations of height and speed above the ground. Characteristic features of the eVTOL configuration, such as the propensity for the rotors to be arranged side-by-side, appear to broaden the swath of ground that is affected by these structures (see Figure 1). On the other hand, reducing the size of the rotors and lifting them higher above the ground seems to ameliorate the effects of these features on the vehicle's surroundings. These observations have implications for what constitutes good eVTOL design practice, as well as perhaps for what constitutes the optimal configuration for such vehicles. What this also means is that a range of edge-cases, such as how the aircraft responds to gusts, trims itself during manoeuvres, or responds to a failure of one or more of its drive systems, may all need to be considered in the design and certification of these aircraft in terms of their propensity

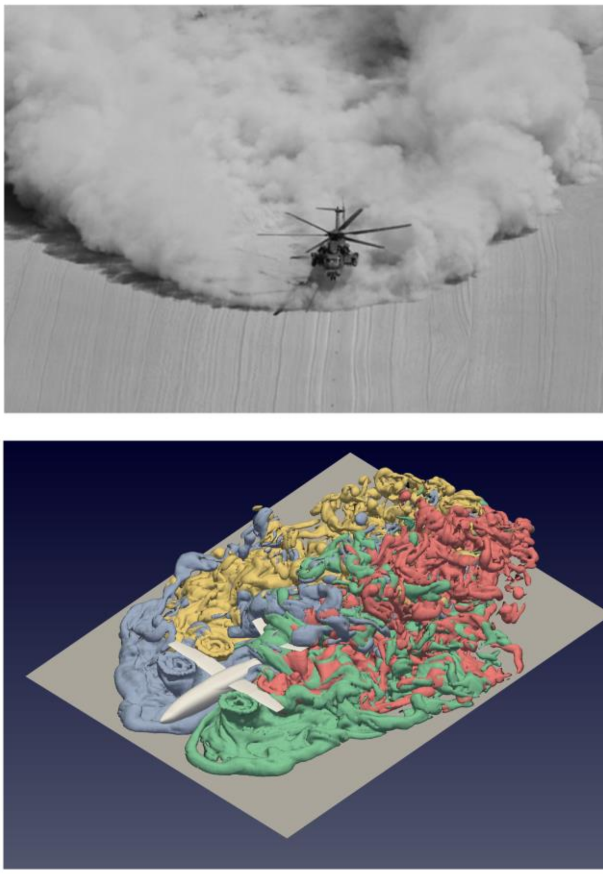


Figure 1: Top: Entrained dust reveals the roller-like structures formed in the flow ahead of a large transport helicopter as it moves forward at low altitude and speed above the desert surface (image source: US Marine Corps). Bottom: similar features are seen in simulations of a notional quad-rotor eVTOL aircraft flying at low speed just above the ground.

to create features in the outwash that, even if only transiently, may propagate outwards and away from the vehicle to eventually cause upset somewhere in its surroundings.

Our final observation has less to do with the influence of the aircraft on its surroundings and instead concerns more directly the influence of the outwash on the vehicle itself. It is clearly apparent that the flows that are created below the aircraft during its interaction with the ground have a strong influence on the controllability, stability and ride comfort of the vehicles themselves. These flows are generally highly unsteady, and can lead to buffeting and vibration, to non-linear changes in the response of the vehicle to control inputs as the vehicle accelerates from hover into forward flight, and potentially to a range of other pathological aerodynamic phenomena that depend on the details of the aircraft's design. Although the present study has allowed us only to scratch the surface in terms of investigating the range of aerodynamic phenomena that eVTOL aircraft might exhibit when operated close to the ground, it is hoped that the few examples presented later in this report will be indicative of the challenges that will be faced by designers and operators alike in constructing a safe, docile transportation system that is suitable for regular, reliable operations with paying passengers on board.

3 What do our findings mean practically for the aviation community?

The prime consideration that the aviation community needs to be aware of is that eVTOL aircraft will have distinctly different outwash characteristics when compared to the helicopters on which most of our current understanding and experience is based.

3.1 Designers of eVTOL aircraft

In this light, the designers of eVTOL vehicles would do well to acknowledge the limitations in the applicability of the published knowledge base to their particular class of aircraft and to adopt the appropriate specialist tools that will allow them to quantify accurately the shape and strength of the outwash field that their vehicles will create when operating close to the ground. They would also do well to implement procedures that will allow them to provide accurate information regarding the consequences of their design decisions to the regulators and operators of their aircraft, at least as far as the dangers posed by the outwash that might be created by their vehicles is concerned. They will also potentially need to be ready to mitigate any pernicious features of their products by incorporating this predictive capability into their design practice, and to consider a broader range of pathologies and edge-cases than is presently the case when ensuring that their aircraft are safe to operate under all possible operational conditions.

3.2 Operators

Operators will need to be aware of the specific dangers that the aircraft in their particular fleet might pose to surrounding infrastructure, equipment and personnel, and to account for the shape and strength of the outwash field that is generated by their particular aircraft in defining the procedures that their fleet should adhere to during its everyday operations. Small changes to procedures, together with an improved understanding and situational awareness of what is happening in the air surrounding the vehicle at any point along its trajectory, may have large positive effects on the safety of operations.

3.3 Infrastructure designers and developers

Infrastructure designers and developers may have to adopt a more nuanced and all-encompassing understanding of the characteristics of the outwash that this new class of aircraft will produce, particularly in terms of its likely influence on vertiport dimensioning and layout. Some designers may potentially have to modify their expectations regarding the density and tempo of the operations that might safely be possible from their facilities. This will especially be the case where projections as to what might be possible have been developed solely on the basis of experience with conventional helicopters. Indeed, in an industry that is governed by standards, and guided extensively by codes of practice, it is very likely that some of these codes and standards will need to be upgraded in the light of the new understanding of the dangers posed by outwash to personnel and infrastructure that will emerge from this and other studies that might lead on from it.

3.4 Regulators

Regulators, in exercising their responsibilities in terms of creating, maintaining and enforcing the codes that govern both vehicle and infrastructure design, and in overseeing safe operational procedures and standards, will need to internalise the fact that eVTOL aircraft have their own particular aerodynamic characteristics, as distinct from those of the traditional forms of rotorcraft for which they have been responsible in the past. This realisation will undoubtedly complicate the process of extrapolating from the known behaviour of existing aircraft classes when constructing the new regulations and standards against which eVTOL aircraft will be certified as safe for commercial operations. Indeed, an improved understanding of the particular characteristics of this new class of aircraft is essential if the regulators are to play an educated role in defining the most effective and comprehensive procedures for validating the safety of this new class of vehicles. When it comes to formulating the framework that will eventually be required to support effective regulation of eVTOL aircraft, we hope that the underlying principle that we have tried to embody in this work will be a useful guide - namely that by abstracting the key generic features of the problem so that the effects and characteristics that are pertinent can be readily discerned from those which are not, a coherent and unambiguous set of guidelines can be produced that can then be used across the industry to ensure its safety.

3.5 The aviation community as a whole

Finally, it is hoped that many practical engineers might accept the challenge that is implicit in the very structure of the present study. In the absence of a body of directly-relevant, real-world data, the study has been confined largely to the domain of theory and numerical experiment. The first challenge is for interested parties thus simply to engage with the work, and to test its findings and assertions against their own experience and knowledge. Through the ensuing debate, we stand to strengthen the rigour and depth of our understanding. Secondly, aircraft manufacturers and research institutions, especially those who have the wherewithal to make relevant real-world measurements, should perhaps consider putting to one side any qualms over ownership or commercial advantage and joining in a fuller initiative that is founded on a genuine wish to understand and overcome the potential problems for the industry that our work has highlighted. Unstructured and ad-hoc data collection for its own sake is furthest from our mind however – we are advocating a proper investigation of the phenomenon that is founded firmly on the Scientific Method. Indeed, this study provides some pointers as to how this investigation might be structured. The hope is that, in engaging with the issues that are raised by the work presented here, we all contribute to the safety of the eVTOL community as a whole.

4 What we have done

4.1 A new study

This report describes the outcome of a fundamentally new study in which the primary aim was to gauge the range of aerodynamic effects that would manifest in the outwash that is created by eVTOL aircraft, and, indeed, to establish how the properties of the vehicle’s outwash depend on the details of its geometry and operating state. The study has aimed to be as generic as possible in its outlook, its goal having been to establish the basic trends and dependencies associated with this category of aircraft when defined as broadly as possible. Our intent has been to provide guidance to manufacturers and operators alike. Importantly, we have endeavoured to present our results without favour being shown, or aspersion being cast, on any one particular manufacturer's product or on any one particular design concept - although in this vein, where necessary, we have not held back from pointing out the strengths and deficiencies, as well as the potential hazards and advantages, associated with particular geometrical configurations and means of operating these vehicles. It is hoped that in a later study our findings presented here will be expanded into a fuller set of design heuristics and rules for good practice, and even, potentially, into a generic model that can be used during the design process to forecast the range of outwash effects that are likely to be created by any particular choice of configuration or operating practice.

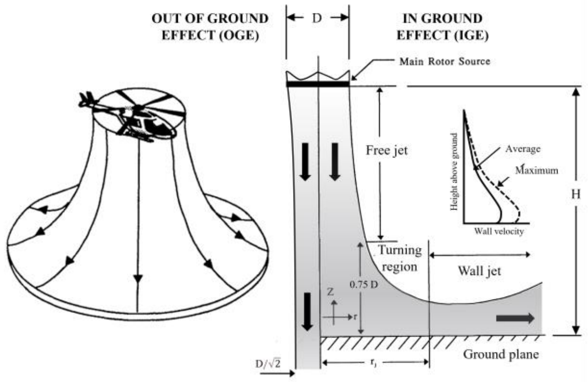


Figure 2: Simple model for the flow in the outwash below a hovering rotor, as per Ferguson[1] and Preston[2].

4.2 Finding a common thread

To achieve our stated goals, we have examined the background literature and used this to construct a hypothesis for how the outwash below a generic eVTOL aircraft depends on the operational state of the vehicle and its configuration. Based on this hypothesis we have conducted a series of numerical experiments on a range of aircraft configurations. The set of configurations that were simulated during the course of this study was constructed to be representative of the breadth of eVTOL design practice, the aim being to find a common thread that can be used to organise and codify our understanding of the outwash characteristics that are peculiar to eVTOL aircraft as a generic class of vehicles. The principal utility of this part of the work will be to inform progress towards regulation and certification of the various aspects of the eVTOL industry that pertain to the safety of operations near to installations and personnel on the ground.

4.3 The most appropriate tools for the task at hand

To be able to characterise the aerodynamic behaviour of this range of aircraft configurations, we have used a numerical tool, called the Vorticity Transport Model[3,4] (or VTM), which is capable of producing very highly resolved and accurate renditions of the evolution of those structures within the airflow below the aircraft that are known from previous experience[5,6] to be primarily responsible for the observed and practically-relevant characteristics of the outwash. These characteristics include the spatial extent of the outwash, its strength and its inherent unsteadiness, as well as more qualitative measures - such as whether the flow in the outwash is sheet-like or jet-like in character, or whether it is turbulent or smooth. We have used this numerical approach quantitatively to compute the unknown coefficients in our model for how the strength of the outwash might depend on the operational state and configuration of the vehicle, and thus to provide a comparative assessment of the strength of the outwash that is produced by vehicles with different design. From a more qualitative point of view, we have used the same model's detailed renditions of the flow field near the aircraft as it develops and evolves over time to explore the range of aerodynamic and flight-dynamic phenomena that aircraft with different configurations might exhibit when operating close to the ground. The aim here has been to obtain insight into the fundamental physical processes at work that might inform a more comprehensive future study, especially one that aims to encapsulate our understanding in a set of generally-applicable physical principles or design heuristics.

4.4 Limitations of the study

Its authors will be the first to acknowledge that this study has amounted to little more than a short, broad-brush, preliminary exercise - the domain that needs to be investigated is huge, and many physical effects and contributors to the particular aerodynamics of this class of vehicle remain open for exploration. Indeed, many of the questions that were raised by the study itself remain to be answered. Nonetheless, we hope that some of the outcomes of this study will be instructive, revealing, and even educational, especially to those within the eVTOL community who may have to deal with the practical consequences of the particular aerodynamic environment that these vehicles will create in the air that surrounds them.

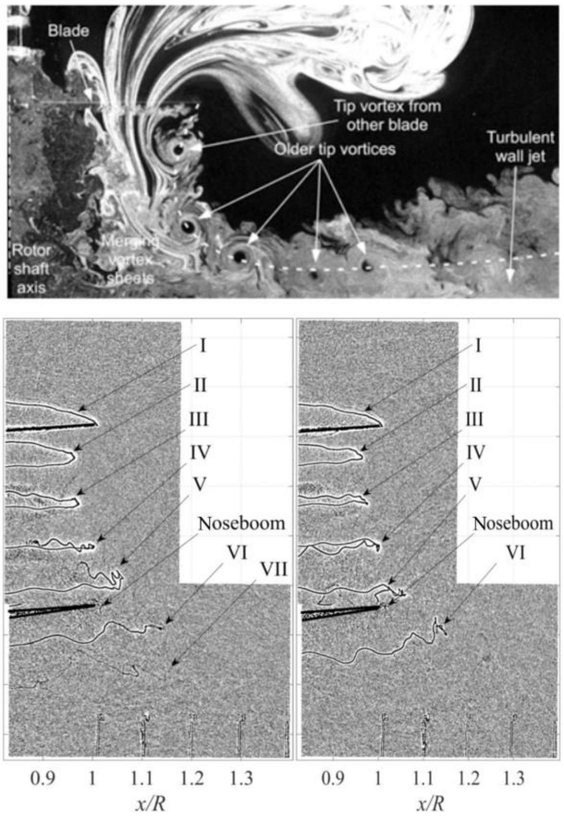


Figure 3: Experimental visualisations showing how the rotor wake is comprised of discrete vortical structures. Top: small-scale experiment[7]. Bottom: full-scale measurement[8].

It is important thus to acknowledge the limitations of the current study and to provide some pointers towards what should be done in future. In the present work we have concentrated largely on describing the connection between the morphology of the outwash field and its relation to the geometric configuration and the operational state of the aircraft. We have also shown the connection between the morphology of the outwash field and the associated velocities that might be experienced by observers located in the aircraft's surroundings, particularly where this connection contributes to a basic understanding of the relevant physics. We have concentrated however on a description of the flow in terms of the dynamics of the vorticity that it contains rather than in terms of the velocity more directly. It is our firm conviction that this approach, through exposing the 'bones' and 'ligaments' of the flow, reveals better its inherent structure and dynamics than would any description in terms of the velocity field more directly. Finally, we have examined in detail the aerodynamics of only a very few of the possible configurations available to the designers of eVTOL aircraft – our results are thus suggestive of the behaviour of the class of aircraft as a whole, but can hardly be construed as comprehensive or encyclopaedic.

Where we have paid attention to dynamic conditions, we have emphasised the presence of wake impingement on the airframe where it is apparent in our simulations, but, given the extensive historical record of aerodynamic interactions between the propulsors, the airframe and the ground in exciting various pathological and even dangerous aircraft dynamics, our analysis falls short of doing this important topic full justice. Our analysis hopefully does however portray very compellingly the complexity of the aerodynamic interactions that occur between the various components of eVTOL aircraft, particularly those that have multiple propulsors, and provides sufficient pointers to indicate where further work would most effectively be directed.

Finally, the derivation of design heuristics and guidelines would be an important outcome of a more comprehensive study. The designers of eVTOL aircraft will hopefully find much information to ponder in this report, but the direct guidance to them that we provide is inherently constrained by limitations of time and space that are consistent with the preliminary nature of this study. If Kuhn and co-workers at NASA and McDonnell-Douglas had several decades[9] to develop their insights into the aerodynamic characteristics of jet-lift and V/STOL aircraft, perhaps we can be forgiven for our relatively cursory exposition of the analogous eVTOL theory, especially given the very few months of effort that we have so far been able to devote to the topic.

5 Background information

In forming our conclusions, we have relied upon a substantial body of prior research and investigation into the aerodynamic characteristics of vertical-lift aircraft when operating close to the ground. The body of research that we have exploited can be organised productively into four, partially overlapping themes:

5.1 Helicopter-related work

A large body of experimental, numerical and theoretical information has been derived over the years to explain and characterise the properties of the outwash field that is produced by conventional helicopters. Indeed, this body of work forms the fundamental intellectual “stepping-off point” for the analysis that we have conducted in this new study.

In terms of providing a basic physical model for the behaviour of rotorcraft operating close to the ground, the most influential work within the helicopter community, by far to date, has been the report that was produced by Ferguson[1] as the culmination of a comprehensive study for the Federal Aviation Administration (FAA) that was undertaken in the early 1990s. Ten years later, the original work was improved and extended by Preston and co-workers[2] at the US Army Research, Development and Engineering Command (AMRDEC).

The outcomes of these studies were presented in a format that was intended to make the material contained therein as practically useful as possible, and indeed the published output of these studies has underpinned much of the rotorcraft community’s current practical approach to understanding and mitigating the effects of downwash and outwash. The material provides detailed and quantitative means of assessing the risks posed to personnel immersed in the outwash, and for estimating the hazards posed by flying debris that helicopters might lift into the air. To achieve this end, a comprehensive semi-analytic model of the aerodynamics of lifting rotors is also presented that allows those characteristics of the outwash below helicopters and tiltrotors that are particularly salient to the operational safety of these vehicles to be estimated.

Given how influential this work has been in shaping the outlook of the rotorcraft community in terms of the risks posed by helicopter outwash, it is important that some of the deficiencies in the conceptualisation of the rotor wake that is presented in these studies are carefully explained. It is important to point out that several of the issues that are catalogued below have been acknowledged by the authors of the works themselves, but it is our belief that the impact of some of these deficiencies on our ability to accurately assess the dangers posed by the outwash have been under-emphasized up to now. This issue takes on particular relevance when it is appreciated that some of our findings may be viewed as somewhat counter to the established wisdom that is contained in these works.

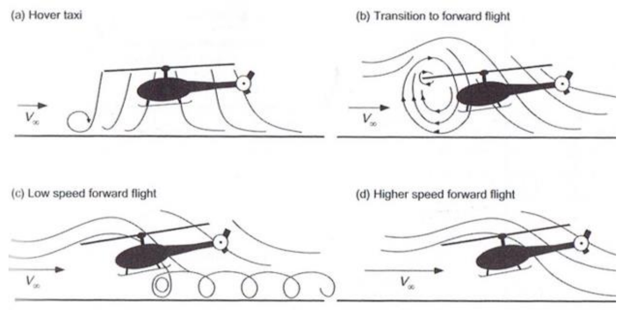


Figure 4: Schematic showing the changes in the structure of the outwash field below the helicopter as the vehicle accelerates into forward flight at low altitude above the ground. At the lowest forward speeds (b), the flow is characterized by a large zone of flow that re-circulates through the front of the rotor. As forward speed is increased, this re-circulation concentrates to form a bow-shaped "ground vortex" just above the ground in front of the aircraft. As forward speed is increased further (c), this ground vortex moves under the aircraft, eventually dissipating as the wake of the helicopter is swept back behind the aircraft and lifts clear of the ground (d). (Figure adapted from Ref. 10.)

Indeed, in the light of the widespread use that is made of Ferguson's and Preston's works throughout the rotorcraft industry, we were initially left in somewhat of a quandary as to how best to frame some of the findings of our new study. In departing too far from accepted wisdom there is always the danger of being perceived as contrarian or iconoclastic instead of rigorous and insightful. After careful consideration, the most sensible approach to adopt seems to have been two-fold. For the most part, we have used Ferguson's representation of the flow in terms of its underlying statistics as a useful way of encapsulating very large quantities of data in more compact form than would otherwise be possible, but, where we *have* adopted this approach, we have also been careful to place the analysis in its proper context by attaching the appropriate caveats. Elsewhere, we have been very careful to provide specific instances and examples rather than falling into the trap of over-generalisation that a statistical or otherwise-homogenised representation of the data would allow.

The fundamental flaw in the modelling approach that is adopted within these two influential studies is that it is founded on a conceptualisation of the outflow as a turbulent jet (revealing, indeed, the foundations of the analysis in the jet-lift literature that is described in more detail below). Notwithstanding semantic quibbles over the difference between "wakes" and "jets", this conceptualisation implies a continuity and smoothness within the outwash field that is belied by more modern experimental and numerical work (see Figure 2). Modern studies reveal the very discrete, and in some cases even intermittent, nature of the flow out across the ground below a hovering helicopter.

Indeed, a more nuanced, modern understanding of the structure of the helicopter outwash field views its evolution and behaviour in terms of the propagation, interaction and decay of the coherent vortical structures that are produced in the wakes of the aircraft's propulsors[12] (see Figure 3). The danger of the approach that is followed in Preston's and Ferguson's works is that it potentially mis-represents the effect, then, of the compact, transient features in the flow that numerical simulations, together with some experimental studies, predict will have the most damaging effects on the aircraft's surroundings.

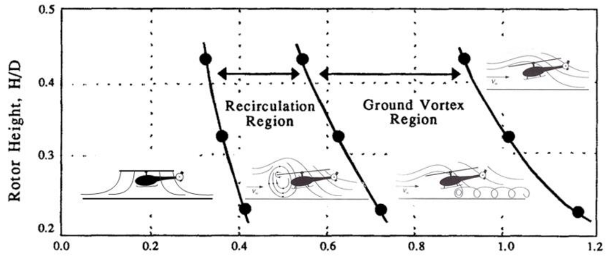


Figure 5: Curtiss's diagram showing how the flow below the rotor can exist in one of several states, depending on the altitude and speed of the system above the ground[11].

The conceptualisation of the flow as a turbulent jet also leads very naturally to a statistical representation of the flow, at any particular radial location within the outwash, in terms of a mean velocity profile onto which a series of fluctuations can be superimposed. The temptation is then to describe the fluctuations at each radial station in terms of a statistical distribution of velocity perturbations about this mean flow. Apart from denying the possibility of correlation between what happens in one part of the flow and another, this statistical treatment is rather simplistic and naïve in several other respects. Indeed, excessive importance is given to statistically non-robust measures such as the maximum measured outwash velocity, and the assumption is made, in the absence of any substantive basis, that the fluctuations within the turbulent jet follow a normal distribution about the mean velocity. This particular assumption egregiously mis-represents the frequency of the extreme but relatively rare events (in our case, and as we shall show later, caused by the intermittent ejections of large boluses of concentrated vorticity from certain locations within the flow underneath the vehicle) that we now know are likely to do the most damage as they propagate outwards into the flow surrounding the vehicle.

Figure 6: The Vought XC-142A - an experimental V/STOL aircraft from the heyday of VTOL research in the 1960s. Top: the aircraft in hover mode, bottom: the aircraft in forward flight. (Image source: NASA)

A particular concern surrounds the effect of these perturbations on the behaviour of personnel that might be immersed within the outwash. The conceptualisation that arises from a study of these works is of an encounter with the outwash below a rotorcraft being somewhat akin to being immersed in a relatively uniform flow of air that extends to some height above the ground, albeit with some superimposed buffeting[1,2]. Indeed, at the heart of Preston's and Ferguson's conceptualisation of the effect that immersion in the outwash will have on personnel going about their business near to an operating rotorcraft is the idea that the flow will cause an overturning moment that simply needs to be resisted in order for the affected individual to retain their composure. Very little cognisance is given in these original works of the possible effect of sudden, unexpected gusts of air in causing upset that is incommensurate with their strength, or of the possibility that certain types of transient excitation[13,14] within the outwash might cause forms of upset that the human physiology is very poorly adapted to counteract (especially in the presence of infirmity or frailty[15] – in other words, well outside the military context in which the analysis was originally framed). These issues all have very direct relevance when considering how eVTOL aircraft might interact with their environment, particularly during passenger embarkation and disembarkation.

On a more positive note, as part of their investigations, these studies managed to collate a large body of experimental data which, up to the time of publication of the work, had remained dispersed and largely inaccessible to non-US researchers. This collection of data has proved to be very useful to subsequent authors, us included, in validating various attempts to characterise numerically the physics of the outwash field. Somewhat disappointingly, however, the dataset is confined to large, heavy military rotorcraft such as the CH-47, CH-53, UH-60 and V-22, and the extent to which the data applies to the very much smaller rotor systems that are characteristic of eVTOL aircraft is by no means clear.

Figure 7: The VFW-Fokker VAK-191B, one of the more complex jet-lift aircraft that was built and flown in the 1970s. The vehicle is shown here in hover – a wet runway revealing some of the effects on its surroundings of the resultant outwash from the six nozzles that were used to sustain the aircraft in vertical flight. (Image source: VFW-Fokker.)

In terms of resolving and understanding the complexities in the flow within the outwash below a hovering helicopter, some of which have been alluded to above, a scattered body of largely uncoordinated experimental and numerical studies exist. Despite their lack of clear programmatic coherence, these various studies have distinct value in revealing some of the details of the flow, or in providing detailed measurements against which numerical predictions can be verified. Notable in this respect are the works of Leishman *et al.* [7,16] and Ramasamy and Yamauchi[17] which stand out through their particularly careful attention to accurate data reduction, and their focus on characterising the behaviour of rotor systems that have been especially devised to be simple enough so that the pertinent features are not obscured by the various extraneous effects that might be introduced when modelling more "realistic" systems. These works have proved particularly useful in establishing the validity of the numerical approach that we have taken to modelling the aerodynamics of eVTOL aircraft and to anchoring its predictions firmly in physical reality.

A second body of experimental data exists that deals with the physics of rotor wakes when in forward flight rather than just when in hover (see Figure 4). Curtiss was one of the first researchers to show that the wake of a conventional helicopter rotor could exist in one of a range of states depending on the height of the rotor and the speed of the helicopter's forward motion above the ground (see Figure 5).

His experimental work[11] was later put on a firmer intellectual footing through the use of numerical simulation to reveal the basic role of vortical instability in promoting the evolution of the wake from each state into the next as the critical speed for the relevant transition was attained by the helicopter[5].

These particular works formed the intellectual basis for several elements of the present study, and especially when considering the effects of the height of the aircraft above the ground and its forward speed on the structure and behaviour of the outwash below the vehicle.

5.2 Tilt-Rotor and Multi-copter studies

The use of electric propulsion as a fundamental constituent of the design of eVTOL aircraft motivates, for good physical reasons, towards the use of multiple, small motors, in most cases each driving their own propulsive rotor or propeller. Although this proliferation of propulsors might be viewed as a very recent departure from conventional helicopter practice, with its preference for lift to be provided via a single, large main rotor, the multi-rotor concept is not new. In fact, the first device that was ever considered to be a practical rotorcraft[18], Cornu's design of 1907, had twin large rotors in what we would now call a "tandem" configuration. In recent decades, interest in tilt-wing and tilt-rotor aircraft (usually with two to four relatively highly-loaded propulsors) has increased as a way of blending helicopter-like performance in hover with the advantages of the turboprop commuter-liner in terms of range, speed and endurance in forward flight. Aircraft such as the V-22 Osprey[19], currently in service with the US armed forces, and the AW609 civil tilt-rotor that is currently undergoing certification[20], are representative of this type of aircraft. Many of the development programmes associated with these advanced rotorcraft have left a legacy of useful numerical and experimental data which can be used to inform our current thinking. The US Army's Joint Heavy Lift programme[21] of the early 2000s is notable in this respect, having provided some compelling evidence for the complexity of the aerodynamic behaviour of the outwash field below large, heavily-loaded quad-rotor vehicles, both in hover and in forward flight[22,23].

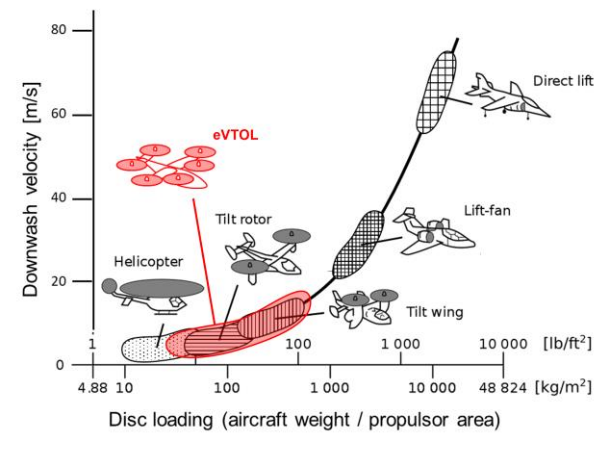


Figure 8: eVTOL aircraft have higher downwash velocities than helicopters, but the velocities in their downwash are not as high as those that are created by some advanced VTOL concepts. (Figure adapted from Ref. 30.)

These historic vehicles were generally equipped with far fewer propulsors than the number to which electric propulsion concept drives the design of modern eVTOL aircraft - their aerodynamics is generally thus very much simpler. Despite this, some of these earlier studies have provided us with a solid basis on which to verify and validate our approach – indeed, to the point where we have felt confident enough to extend our analysis to the more complex aerodynamic problems that are potentially posed by eVTOL aircraft.

5.3 Historical V/STOL research

Although many of the innovations that are embodied in the current generation of eVTOL aircraft mark a radical and innovative departure from historical thinking, it is also the case that equally many of the concepts that have been considered, or are currently under development, have their antecedents in the long history of the development of vertical and short take-off and landing aircraft (V/STOL aircraft) that has continued in fits and starts since the early years of the last century[24,25,26]. In some cases, the design of modern aircraft is directly inspired by historical precedents, in other cases it seems that older ideas have simply been re-discovered. The relevance of this body of work to the current study was to sensitise us to the possibility that some of the aerodynamic effects that were a characteristic of these legacy designs[27,28] might also manifest in the behaviour of the current generation of eVTOL aircraft, thus guiding our investigations and allowing it to be focused in a few key areas. For instance, the complex vortical flows that were produced in the junction between the ground, the wing and the fuselage in the case

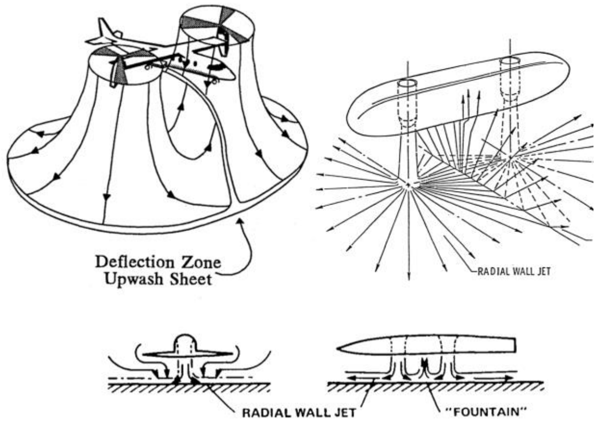


Figure 9: The outwash below an aircraft that has more than one propulsor – some simple representations taken from the works of Ferguson[1] (top left) and Kuhn and co-workers[9,37].

of the Vought XC-142 (see Figure 6) were implicated during early wind-tunnel tests[29] as likely to cause significant handling qualities and stability problems if the aircraft were to be operated close to the ground. Subsequent flight testing confirmed these projections[30]. Our numerical experiments showed very similar effects to be present in the aerodynamics of some of the configurations that we analysed, leading us to surmise that similar dynamic effects might characterise the behaviour of some of these aircraft when operated close to the ground.

5.4 Historical Jet-Lift research

A very large body of experimental, theoretical and semi-empirical work has been amassed over the years in the jet-lift community as part of the long-standing effort to adapt gas turbine propulsion to providing an efficient means of vertical take-off and landing (see Figure 7). Some of the considerations faced by the designers of jet-lift aircraft such as the F-35 and Harrier are analogous to those faced by the designers of eVTOL aircraft - for instance the need to match good performance in hover with efficiency in forward flight[32]. The very different levels of performance that are expected from the two different classes of aircraft has meant, however, that the jet-lift literature has needed to be re-interpreted to some extent before being used to try to understand the aerodynamic features of eVTOL aircraft as they interact with the ground. Figure 8 shows for instance that eVTOL aircraft are significantly more benign than jet-lift aircraft in terms of the strength of the downwash that they are likely to produce, and, indeed, practical considerations[33] that garner a tremendous amount of attention within the jet-lift community, such as ground scouring, hot gas ingestion, and the effects of supersonic flow in the efflux of their propulsors, have, at most, only weaker analogues within the eVTOL aerodynamic domain.

Despite the effort needed to re-interpret the jet-lift literature before it is applicable within the eVTOL context, this exercise has proved to be foundational in structuring the present study. In addition to a range of highly-relevant experimental data[34] that deals with fundamental fluid dynamic issues that are common to both domains, such as the evolution of fluid dynamic structure within the jets that are created by the propulsors[35], and what happens when the out-flows from several jets interact as the flow spreads out across the ground[36], there also exists an extensive basis of semi-empirical work (exemplified by the work of Kuhn and collaborators at NASA[9,37], and codified in design tools[38] such as McDonnell Douglas's widely-exploited suite of ground interaction models). As such, the contribution of this body of work to the present study has been fundamental - firstly, in exposing the range of issues that might need to be considered, secondly, in suggesting the form that a systematic approach to the characterisation of the aerodynamics of eVTOL aircraft might take, and, thirdly, in providing some of the theoretical basis for distillation of the results that were obtained (see Figure 9).

6 Gaps in the literature

The ideal situation would be if we could simply rearrange the published literature into a new format that would allow us to understand the likely characteristics of the outwash that might be generated by eVTOL aircraft. Given the analysis that has been presented above, it should be reasonably clear that this cannot be the case. Although eVTOL aircraft share many characteristics with various other forms of flying machines, the overlaps that are meaningful from a quantitative, rather than simply from a qualitative, point of view are few and relatively far between. Differences in disc loading, number of rotors, and the juxtaposition of these rotors around the airframe when compared to more classical aircraft, and even when compared to the broad variety of historical VTOL aircraft, are a few of the more obvious reasons why eVTOL aircraft occupy their own, distinct aerodynamic niche.

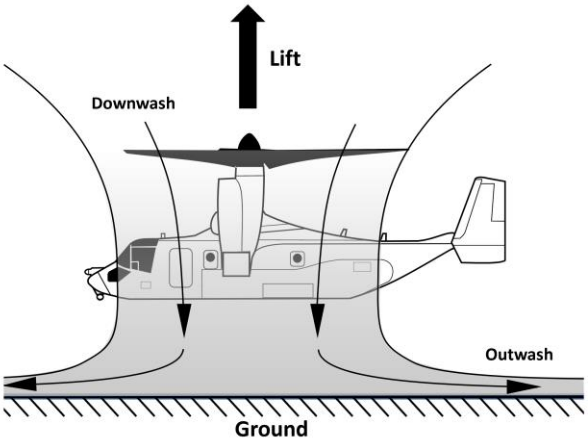


Figure 10: The outwash across the ground below a hovering aircraft is caused by the deflection of the air that is accelerated through their propulsors in the process of generating lift. (Figure adapted from Wikimedia Commons.)

It is clear too that quantitative understanding of many of the pertinent aerodynamic phenomena falls short in many respects of what is required to fully understand the basic physical mechanisms that are at work in the outwash of a vehicle as complex as a multi-rotor eVTOL aircraft. This lack of defensible quantitative insight arguably extends back to a pervasive mis-conceptualisation of how the wake below an isolated rotor actually develops to form the outwash below the system. Certainly, when it comes to a broad understanding of how the outflows from multiple rotors interact on the ground, the published record is almost silent. Published work revealing the aerodynamics of actual eVTOL aircraft when operating near to the ground is particularly scant, and in many cases the record is contaminated by analyses where, either by design or omission, more general insight into the aerodynamic characteristics of this class of vehicles has been obscured.

This study takes one small step towards filling this void by providing an advanced description of the relevant aerodynamic phenomena that is based on our latest understanding of the salient physics. It then concludes by providing a set of openly-available data regarding the outwash characteristics for a range of eVTOL aircraft configurations where pains have been taken to be agnostic to any particular commercial concerns. Indeed, an important characteristic of the work that is presented in this report is that we have used our scientific and engineering judgement and experience to simplify both the physical and the geometrical representation of the system to the point where a range of useful pointers have emerged as to the generic aerodynamic characteristics that this class of vehicle will exhibit when operated close to the ground.

7 Basic Concepts

7.1 What is outwash?

The defining characteristic of helicopters, tilt-rotors and many eVTOL aircraft is their reliance on a set of propulsors to generate most of the lift that they require when operating at low forward speed, and particularly when hovering. The propulsors themselves can take on many forms, from open propellers, to rotors in ducts, to complex fan-like devices that are more akin to small gas turbines. Whatever their particular type, the common feature that is shared by the propulsors of these aircraft is that they all generate lift by accelerating the column of air that passes through them downwards into the flow below the vehicle. The pattern of downwards-moving air that is created below the vehicle by all its propulsors in the process of generating lift is called the *downwash field* (see Figure 10). When the downwash field comes into contact with the ground, it is deflected radially outwards below the aircraft to form the *outwash field*.

7.2 Helicopter experience shows the outwash field to pose a range of hazards

Operational experience with helicopters and tilt-rotor aircraft has shown that circumstances exist where the flow velocities in the outwash field can become high enough (or unsteady enough) to be problematic.

7.2.1 Hazards to the helicopter's surroundings

Typical problems associated with high velocities in the outwash field of helicopters and tilt-rotors include the possibility of:

- uplift of debris and other objects from the ground - in some cases the velocities within the outwash field can be high enough to turn loose objects into dangerous projectiles;
- discomfort, physical upset and injury to personnel and other bystanders who may find themselves caught up in the outwash field; and
- damage to ground facilities and to other aircraft that might happen to be parked or operating nearby (see Figure 11).

If the composition of the surface below the vehicle is conducive, then the interaction of the outwash with the ground can also cause particulate matter on the ground to be lifted into the flow around the aircraft. Under such conditions, the pilots' visibility of their surroundings can become obscured, causing a loss of situational awareness, and leading to the onset of a phenomenon that is called brownout when the surface of the ground is sandy or dusty[6], or whiteout when the ground below the vehicle is covered in snow.

A particular concern is that some eVTOL aircraft might induce even higher velocities within their outwash fields than those that are generated by more conventional rotorcraft, amplifying the effects of the outwash that is generated by eVTOL aircraft beyond the levels that are already associated with helicopter operations.

7.2.2 Hazards to the helicopter itself

It is important to realise that the aerodynamic interaction of the propulsors with the ground not only influences the surroundings of the aircraft, but that the flow within the outwash field can also interact with the aircraft itself and interfere with its dynamics, stability and control.

Some typical problems that are encountered when this happens in the context of helicopter operations include:

- buffeting and vibration of the airframe;
- reduced static stability, particularly about the pitch and roll axes of the aircraft;
- changes in dynamic stability (*e.g.* shifts in the frequency and damping of natural modes); and
- non-linear control response, especially during the acceleration of the vehicle from hover into forward flight.

It is very likely that analogous effects might afflict the dynamics, stability and control of eVTOL aircraft, and indeed that these effects might be exacerbated by certain aspects of their design and operation.

7.3 The outwash that is generated by eVTOL aircraft might be more of a hazard

We know from simple physical arguments that the major factor influencing the strength of the downwash field is the disc loading of the propulsors, defined as the ratio W/A of the weight W of the aircraft to the total area A of all the propulsors providing lift to the vehicle.

7.3.1 What can we learn from published eVTOL data?

In analysing the design characteristics of the current generation of eVTOL aircraft and comparing these to the properties of more traditional helicopter designs, a divergence in design approach quickly becomes apparent. Figure 12 shows the relationship between disc loading and weight for a representative selection of historical helicopter designs, revealing that most conventional helicopters obey a particularly well-defined trend (which can be explained in terms of the square-cube law that relates the mass and the area of a homogeneous body). A notable exception to the rule is the V-22 tilt-rotor aircraft, where a conscious decision was made to use very highly-loaded rotors in order to produce a large transport vehicle that was still compact enough to fit onto the decks of naval vessels[19]. Despite the fact that, for obvious commercial reasons, eVTOL manufacturers tend to keep the true weight of their aircraft fairly close to their chests, Figure 12 also contains disc loading data for a range of eVTOL aircraft for which published information can be verified and trusted. In comparing the data for the two different types of aircraft, it is clear that, if the disc loading of any current eVTOL aircraft design is compared to that of a conventional helicopter that has the same weight, then it will invariably be the case that the eVTOL aircraft has substantially higher disc loading. As shall be shown shortly, higher disc loading leads inevitably to higher downwash velocities through the propulsors.

Figure 11: The velocities in the outwash field below a conventional rotorcraft can be high enough to cause problems to infrastructure and personnel nearby. (Top: uplift of debris; bottom left: damage to ground facilities, bottom right: discomfort and injury to ground personnel. Image source: various.)

At this point we need to be rather careful. The temptation is to equate a higher downwash velocity immediately with the aircraft then producing higher outwash velocities across the ground when the vehicle is operated at low enough altitude for the interaction to be significant. Whether or not a higher downwash velocity will translate into a higher outwash velocity below the aircraft depends in fact on the basis on which the systems are being compared. Whilst it is undoubtedly true that, *all else being equal,* an increase in downwash velocity (and hence disc loading) will translate into an increase in outwash velocity, the simplicity of the argument is confounded by several bedeviling factors, the two most important being, firstly, the influence on the strength of the outwash of the overall size of the vehicle and, secondly, the effect on the structure of the outwash of the format in which the vehicle's propulsors are distributed around the aircraft (what we will call the aircraft's configuration). In terms of assessing the risk to ground personnel and infrastructure, for instance in the context of vertiport design, the fairest results are obtained if the outwash is compared at the same distance from each aircraft. Indeed, an instructive comparison in this respect can be made of the outwash that is produced by two aircraft that are *geometrically identical* up to a scaling factor, where both have the same disc loading and hence produce a downwash with the same velocity. Depending on how quickly the outwash velocities dissipate with distance away from the vehicle, it might be imagined that an observer at a given distance from the larger aircraft will find themselves immersed in a stronger (and possibly deeper) outwash than an observer at the same distance from the smaller aircraft, even though the downwash velocities are the same in both cases. Indeed, such arguments have been used in the past to negate the idea that vehicles as small as the current crop of eVTOL aircraft might pose any threat as far as their outwash velocities are concerned - at least relative to the dangers that are currently tolerated within the helicopter operational community.

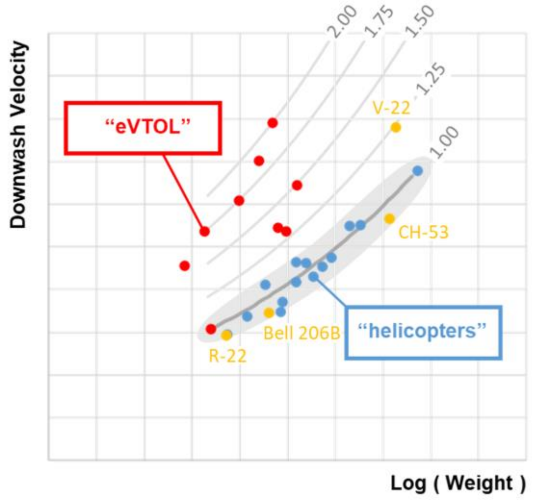


Figure 12: eVTOL aircraft generally create higher downwash velocities than helicopters that have the same weight. (Image adapted from Ref. 39.)

To lend further insight into this argument, the weight and total disc area of the same group of eVTOL aircraft as plotted in Figure 12 are compared in Figure 13. It should come as no surprise that this figure shows eVTOL aircraft generally to be smaller and lighter than the majority of helicopters currently in service – the temptation is thus to expect their characteristics to be more akin to those of light transport helicopters than to those helicopters at the heavier end of the spectrum, and indeed thus for their outwash characteristics to be no more problematic. What is a little more interesting, however, is that the data for the eVTOL aircraft (bearing in mind though the very limited number of vehicles that have been represented in the plot) appear to separate naturally into three distinct clusters.

The aircraft in cluster A are all very tiny aircraft that have disc area and weight much smaller than almost all conventional helicopters. It could indeed be argued that these aircraft are somewhat unlikely to pose a risk as far as their outwash is concerned, given that they lie so far towards the bottom left-hand corner of the diagram where their outwash is likely either to be very weak, or to be concentrated in such a thin layer above the ground as to pose negligible danger.

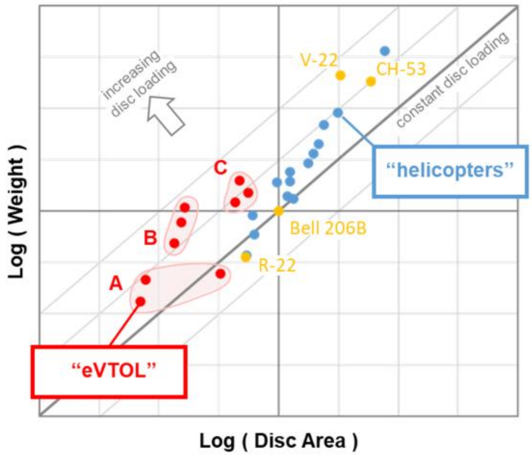


Figure 13: eVTOL aircraft divide into three clusters when their weight and size (as represented by their total disc area) is compared to that of conventional helicopters[40].

eVTOL aircraft in cluster B have weights that are very much in the small helicopter range, but invariably have much smaller total disc area than comparable helicopters with the same mass. These aircraft should perhaps most prudently be treated with suspicion regarding the characteristics of their outwash, in the sense that unfavorable design characteristics (as described in much more detail later in this work) might lead them, despite, ostensibly, their relatively small size, to produce an outwash that is considerably stronger than the outwash that is produced by comparable helicopters with the same weight.

The principal reason why hedging towards a conservative treatment of these vehicles is appropriate in this instance is that disc area is not necessarily the most appropriate measure of the size of an eVTOL aircraft. Indeed, the configurational difficulties that emerge during the process of packing a set of rotors into a small footprint, at the same time as satisfying stability requirements as well as mitigating the potential effects of aerodynamic interactions between the propulsors and other parts of the airframe, can drive the design towards disproportionately larger size than might be suggested on the basis of disc area alone. To an extent this is one of the major themes and findings of this study - that the exact configuration of the vehicle can, under certain circumstances, have a more profound effect on the shape and strength of its outwash than its disc loading alone.

Finally, there exists a small group of eVTOL aircraft, denoted as “cluster C” in Figure 13, which are at least as heavy as the types of small- to mid-sized helicopters that form the backbone of aerial shuttle services today. These eVTOL vehicles tend to have similar, although generally somewhat smaller, overall disc area than the equivalent helicopter, with the result that the vehicles in this cluster have somewhat higher disc loading compared to helicopters that have similar weight. Of all the eVTOL aircraft mapped onto this diagram, the vehicles in this cluster are the most likely to create a strong outwash - potentially, for reasons that will be elaborated on at length in this report, to an extent that will come as a surprise to those whose expectations are founded on their experience of conventional helicopters.

7.3.2 The fundamental question

The fundamental question that needs to be answered then is just how the outwash velocities associated with eVTOL aircraft will compare to those that are produced by helicopters in the same weight class, especially when the effects of aircraft configuration are factored into the argument. eVTOL aircraft are very different to conventional helicopters in terms of their performance and operational characteristics, and this manifests in a very different and, indeed, much more complex aerodynamic environment surrounding the vehicle. This is especially the case when these aircraft are operating close to the ground. This study was conducted to answer this question, and thus to determine just how different the outwash characteristics of eVTOL aircraft are likely to be - especially when compared to those of the helicopters on which most of the community’s experience and intuition, in particular regarding the various potential risks implied earlier, is founded.

8 Philosophical approach

The logic that is required to underpin this line of investigation can be developed considerably further with the aid of some simple theory. We adopt a hypothesis for how the velocities in the outwash field depend on the properties of the aircraft that is responsible for generating the outwash, and then use a simple scaling approach to allow the characteristics of two dissimilar aircraft to be compared. With this result in hand, a simple additional step allows us then to benchmark the outwash characteristics of an entire class of vehicles against those of a given reference airframe – thus, for instance, allowing us to revise our expectations regarding the outwash of eVTOL aircraft on explicitly *quantitative* grounds with respect to our historical experience with helicopters.

8.1 Modelling the outwash

We start with the most basic physical approach to analysing the flow through the propulsors of the aircraft to obtain an estimate of the downwash velocity that is produced by the system. A first-order scaling analysis shows that, with the aircraft in hover, the downwash velocity through the propulsors, V^i, can be expressed in terms of the disc loading (and the air density ρ at the altitude at which the vehicle is flying) as

$$V^i = \sqrt{\frac{(W/A)}{2\rho}} \qquad (1)$$

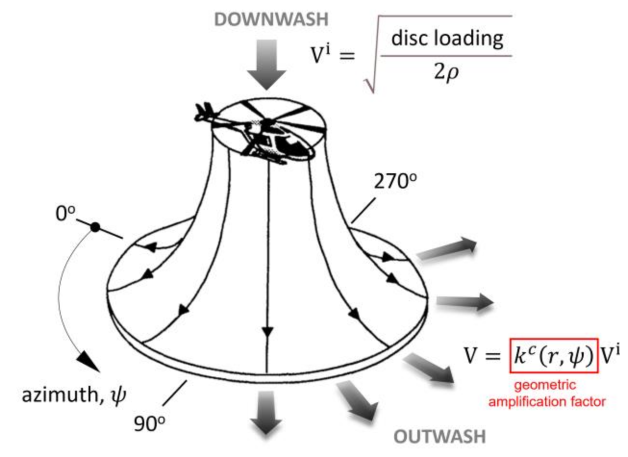


Figure 14: Relationship between the downwash velocity V^i and the outwash velocity V. (Image adapted from Ref. 1.)

This expression is simply a statement of Newton's Second Law of Motion, applied to the fluid as it passes through the rotors, and embodies the fundamental idea that the downwash velocity below the vehicle should scale according to the square root of its disc loading W/A.

It is important to point out, even at this very early stage in the development of the analysis, that various objections can be raised to the use of this expression to characterise the downwash velocity through the system. For instance, if the propulsor is not a pure, unshrouded rotor, or if any of the rotors overlap, then this result must be scaled by an appropriate factor to account for the different rate at which the flow accelerates once having passed through the propulsor. The result also needs to be re-scaled if the lift is not equally shared between all propulsors, or, for instance, if a wing, favourable interaction between the ground and the airframe, or some other stratagem is employed to augment the thrust that is produced by the aircraft. Indeed, even in pure helicopter applications, the direct veracity of this formula relies on the vehicle being sufficiently high above the ground for the flow *through* the rotor to be able to equilibrate with surrounding atmospheric conditions downstream of the rotor. These deficiencies are all compensated for by introducing a geometric amplification factor, $k^c(r,\psi)$, so that the velocity V in the *outwash* across the ground plane (see Figure 14) can be written as

$$V = k^c(r,\psi)\; V^i \qquad (2)$$

The geometric amplification factor k^c in this expression takes into account all the details of the configuration of the aircraft, including not only the size and type of the aircraft's propulsors and their relative juxtaposition, the height of the aircraft above the ground, and so forth, but also, importantly, the distance away from the aircraft, r, at which the outwash is measured. We explicitly retain the dependence of the outwash velocity on azimuth ψ and distance r in the notation given their significance in the analysis to follow. Crucially, we assume that k^c itself is independent of the disc loading so that all dependence on this parameter is contained within V^i.

8.2 A common basis for comparison

What we have essentially done is to assume that all effects of configuration and operational condition on the spatial distribution of the velocity in the outwash field can be subsumed into a simple scaling parameter, but in doing so we need to bear in mind the range of configurational and performance-specific parameters that are encapsulated within the notation. Of critical importance is that the term V^i in this expression, whilst earlier taken to represent the downwash velocity as a measurable, physical property of the system, is downgraded in significance here to the point where it simply embodies the primary influence of the disc loading of the system in governing the strength of the outwash velocity field.

The value of this approach is that if we have to hand a reference configuration for which the disc loading and shape of the outwash field are known, then we can write an expression which allows us to determine the strength of the outwash field of that aircraft relative to that of the reference aircraft:

$$\begin{aligned}\frac{V}{V_{ref}} &= \frac{\sqrt{(W/A)}}{\sqrt{(W/A)_{ref}}}\,\frac{k^c(r,\psi)}{k^c_{ref}(r,\psi)} \\ &\triangleq K_D(W/A)\;K_C(r,\psi)\end{aligned} \tag{3}$$

where K_D is the amplification of the outwash as a result of any difference in disc loading between the aircraft under consideration and the reference aircraft, and, *all else being equal*, K_C is the amplification of the outwash as a result of the differences in configuration and operating condition between the particular aircraft that is of interest and the reference aircraft. We thus have a formal basis for comparison of any two aircraft's outwash characteristics, as long as the geometric amplification factor K_C can be computed. A fairly straightforward extrapolation allows this result to be used to compare the outwash characteristics of the representatives of an entire class of aircraft relative to a particular baseline. For the purposes of the present study, the class of aircraft of interest is the set of all (possible) eVTOL aircraft, and, arguably, the most natural baseline for the comparison is a generic, single-rotor helicopter with conventional disc loading.

8.3 Implementing the analysis

At present, our ability to calculate the geometric amplification factor for any particular aircraft to any level of fidelity is very much limited by the complexity of the underlying physics that gives rise to the outwash field. Thus, at least for the present, we need to resort to other means of establishing this parameter. Fortunately, we have to hand a large body of experience in modelling the behaviour of the aerodynamics of such systems using computer-based simulations of the underlying equations that govern the dynamics of the flow.

9 Numerical approach

9.1 Why use a numerical approach?

Use of numerical simulation to explore the likely characteristics of the outwash field that is produced by eVTOL aircraft has a range of advantages over other means of exploration, such as, for instance, experimental investigation. In retrospect, the ability to iterate rapidly and to conduct a broad range of "what if" studies - at a tempo that has not been constrained by workshop timescales and tunnel settling times - has proved essential to making progress at these very early stages in our conceptualisation of the physics of the outwash field that is created by eVTOL aircraft when they are operated close to the ground.

Indeed, if we can safely presume that our numerical representation of the physical world is of sufficient fidelity to represent accurately those fluid dynamic phenomena that govern the formation and evolution of the outwash field (although, as discussed below, this cannot be taken for granted), then the major advantage of a numerical, rather than a real-world experimental, approach is the flexibility with which existing, new, projected or even just postulated configurational concepts can be created and examined within the virtual world of the computer. This is especially the case when the time and expense of cutting wood or aluminium to shape to create an equivalent range of permutations is considered. Indeed, the numerical approach allows an idealisation of the real world to be created in which issues such as aerodynamic interference between the model and the tunnel walls, overscale representations of certain components, such as drive shafts and motors, and the need for some form of attachment to keep the model in place in the airflow, can all be eliminated. As pragmatic as their existence might be, the unavoidable presence of these features introduces significant error into the measurements obtained during tunnel-based experimental studies.

Perhaps the principal advantage though of adopting a numerical approach is that it allows a degree of abstraction that is not possible in the real world - any of the various effects that are suspected of contributing to the physical behaviour of the outwash field can be simplified, modified or removed completely, allowing for a consistent and structured application of the Scientific Method in exploring the relationship between cause and effect. The end result is a more nuanced understanding of which effects are relevant and which are less so, and a better appreciation of how the various pertinent effects contribute to the overall physics of the problem. Numerical simulations, as a matter of course, produce a densely-packed and rich dataset that covers all the pertinent flow variables, and this allows a view into the details of the flow field, as it evolves, that has a richness that is difficult to reproduce in the real world - especially when budgets are tightly constrained and there are practical limitations on the number of sensors that can be fitted into a small-scale wind tunnel model.

9.2 Real-world data has its utility

This is not to denigrate the utility of real-world data, especially in anchoring and validating our analysis. As such, the present study places us in a very good position to extend our investigations from the numerical domain and into the real world. The temptation needs to be avoided though to treat real-world data as inherently superior to the combination of theoretical and numerical analysis that we have presented here. Many are the examples, especially in the rotorcraft world, where understanding has been retarded, and long-lasting confusion sown, as a side-effect of the pernicious belief that "the real-world data is always right" even in the face of intrinsic errors in the record. These errors are actually quite commonplace and have historically arisen from many sources - ranging from outright mistakes in analysis, through mis-calibration of one or more of the sensors that were used to infer the physical properties of the experimental system, through to failure to detect and accommodate the intrusion of extrinsic but significant confounding effects into the system. The ideal is achieved, of course, when there is a continuous dialogue between theory, numerics and experiment - so that understanding can be cross-checked, verified, and calibrated against existing knowledge and expectations in real time.

9.3 Which numerical approach is most appropriate?

When it comes to representing the physical world to a sufficient level of fidelity for the results of this study to provide meaningful insights into the behaviour of the real-world systems of interest, the choice of numerical approach becomes crucial. The danger is that through not representing the physics correctly, the character and properties of the outwash field that is produced by this class of vehicles may be mis-represented - potentially rendering the outcomes of this work entirely meaningless and irrelevant.

9.4 Velocity-pressure-density formulations

The most common numerical approach that is used in industry and academia presently is to model the governing fluid dynamic equations using velocity, pressure and density as the variables through which the properties of the flow are represented. As shall be explained shortly, this is not the only way of formulating the governing equations, but over the last few decades a range of numerical algorithms have been developed that exploit very effectively the mathematical properties of the set of fluid dynamic equations that follows from this choice of variables. In most of these algorithms, the air surrounding the vehicle is discretised into a grid of small cells, within which the Navier-Stokes equations, which are held to govern the dynamics of the fluid, are solved in approximate form to model the evolution of the flow.

9.4.1 Reynolds-Averaged Navier Stokes (RANS)

The velocity-pressure-density formulation of the Navier Stokes equations has been implemented numerically in many commercial codes, and these codes are used widely within industry as general-purpose tools for characterising the flow over (or through) the full spectrum of systems of engineering interest. The most popular formulation of the governing equations in velocity-pressure-density form is the so-called “Reynolds-Averaged Navier Stokes” (RANS) form. This approach comes about through the realisation that it is fundamentally impossible to resolve structures in the flow that are smaller than the cells into which the flow domain has been discretised. In RANS methodologies, any physics that takes place at sub-grid scales (small-scale turbulence, for instance) is thus represented by modelling its effects “on average” in terms of the scales that can indeed be resolved.

9.4.2 The Velocity-pressure-density formulation (and RANS) has its limitations

The use of the traditional velocity-pressure-density approach introduces several important mis-representations of the fluid dynamics when modelling the aerodynamics of eVTOL aircraft that we have tried to obviate in this study by using a more sophisticated and specialised numerical approach.

Firstly, we know from our earlier work in modelling helicopter rotor interactions with the ground that the aerodynamics is fundamentally driven by the behaviour of the discrete vortical structures that are created by the propulsors of the system in the process of generating lift. The vorticity in these flows evolves from having coherent, tightly-structured sheet-like or filamentary structure near the propulsors, through the disruption of these structures as a result of their fundamental fluid dynamic instability, to their eventual decay and dissolution into a state of disorder that we may term “turbulence”. Accurate resolution of this process is essential if the structure of the flow in the outwash field is to be properly understood and characterised.

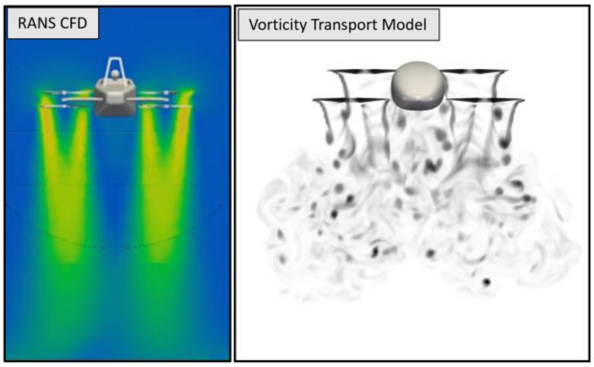


Figure 15: Numerical visualisation of the flow in the outwash/downwash field below a quad-rotor vehicle in a high hover above the ground. The RANS CFD results[41] (at left) are heavily contaminated by excessive dissipation of the vorticity in the rotor wakes. The VTM calculation (at right) does not dissipate the vorticity, and correctly resolves the vortex instabilities that are so important in structuring the flow below the vehicle.

All numerical methodologies that are based on the velocity-pressure-density formulation of the underlying fluid dynamic equations have a distinct problem in representing this process to any degree of fidelity. Essentially, the vorticity has to be inferred from the velocity field, and it can be shown very easily from the mathematical properties of the transformation between these two variables that the velocity field yields a very inefficient and wasteful representation of the vorticity field (conversely, the vorticity field generally yields an extremely compact representation of the velocity field). In practical terms, any structure within the flow, and thus also the evolution of any structure as the simulation progresses, tends to be very poorly represented unless very fine computational grids are used. As a result, the computational burden involved in running a RANS simulation of a multi-rotor eVTOL can be punishing. Indeed, instances abound in the eVTOL literature where under-resolution of the flow has led to very poor representations of the aerodynamic characteristics of the vehicle being modelled (see Figure 15).

Much more important, however, is a fundamental deficiency within the velocity-pressure-density formulation when representing the evolution of vorticity-dominated flows. Indeed, all velocity-pressure-density methods suffer from excessive dissipation of any vortical structures that happen to be present in the flow. The origin of this behaviour is well-understood. Essentially, the kinematics and dynamics of the flow can be encapsulated in terms of a set of conservation principles. The most important of these principles, as far as the structure of the flow is concerned, is that both mass and vorticity cannot be created or destroyed, except at the boundaries of the fluid domain. If any one of these conservation principles is not explicitly encoded into the numerical method, then that method will mis-represent the physics that observance of that conservation principle is supposed to ensure. In the case of a well-constructed velocity-pressure-density methodology, mass is indeed conserved, but the governing equations themselves do not represent the physics to high enough fidelity for the conservation of vorticity to be embodied in the numerical algorithm that is used to model the fluid dynamics. What this means in practice is that the vorticity, instead of following the evolution described above, simply disappears from the calculation as the simulation progresses, with no hope of tracking it or reconstructing its effects on the flow. In present context, this inherent characteristic of this class of methodologies will have catastrophic implications for the resolution of the interactions of the aircraft with the ground, and will seriously mis-represent the complex fluid dynamics that takes place during the interaction between the outflows from the various propulsors and the remainder of the vehicle. This class of numerical methods is thus inappropriate for use in modelling the physics of the outwash that is created by eVTOL aircraft when they are operated close to the ground.

9.5 Velocity-Vorticity Formulations

9.5.1 The Vorticity Transport Model

Given the importance of the vortical structures within the flow in determining both the strength and character of the outwash field below the aircraft, it would seem to be self-evident that the most natural way of representing the aerodynamics in the context of the present study would be to use an approach which (a) directly conserves the vorticity in the flow and (b) models the dynamics of the vorticity distribution itself, rather than inferring the properties of the vorticity field from the values of any of the other flow variables. The Vorticity Transport Model (or VTM) was developed explicitly for this purpose by the authors of this work[3,4], and has been used extensively over the last twenty years to provide a range of fundamental insights into the physics that is associated with the interaction of rotor wakes with the ground. The methodology has been able to explain the existence, for instance, of the characteristic curtain-like features in the brownout cloud that is often produced by helicopters when operating at low altitude above a sandy desert floor[42], and indeed has been used to reveal the existence of additional modes of rotor wake interaction with the ground that were missed in experimental studies of the phenomenon[5]. In the aftermath of significant problems with the V-22 Osprey when in descending flight, the unique features of the VTM were fundamental in exposing the role of vortical instability in precipitating its rotors into a pathological condition called the Vortex Ring State[12,43]. The methodology has also been used extensively within a range of industrial settings to model the aerodynamics of multi-rotor systems[44,45] and has been comprehensively validated against a broad range of experimental data[4,46,47,48].

9.5.2 Other vorticity-based models

The VTM is not alone in the class of numerical methods that have been developed to model directly the dynamics of vorticity field that is created in the wake of a lifting aerodynamic body. The so-called “free-wake” and “vortex-particle” methods both also attempt to solve the same underlying formulation of the governing fluid dynamic equations. These numerical approaches work in a fundamentally different way to the VTM, however. Both of these so-called “Lagrangian” methodologies forego a grid-based representation of the flow domain and, despite the fact that the vorticity is essentially a three-dimensional continuous vector field, discretise the vorticity field instead into a set of discrete elements (either as filaments or as particles), the motion of which is then tracked through time using a suitable numerical algorithm.

9.5.3 The Vorticity Transport Model has distinct advantages

A crucial physical property of the flow in the outwash below the vehicle that needs to be borne in mind, however, is that, particularly when measured in terms of the number of rotor revolutions that need to elapse before any discernible and coherent representation of the long-term behaviour of the outwash field starts to emerge, the flow structures that are produced on the ground are relatively ancient. It is extremely important thus that the evolution of these structures, from their creation on the blades of the propulsors, through their descent towards the ground and throughout their passage outwards across its surface, is accurately and rigorously tracked. In this vein, the VTM relies on an underlying computational grid and the special properties of its numerical algorithm to ensure that the distribution of vorticity within the flow is explicitly, accurately and stably tracked. To this end, a series of concrete measures are available to the analyst that can be monitored throughout the course of the simulation, thus enabling them to verify that accurate results have been obtained everywhere within the flow domain.

This approach has a major advantage in obviating the accuracy and stability issues that tend to plague the Lagrangian methods. Indeed, the Lagrangian methods have an unhelpful propensity to mis-represent the trajectory that is followed by the vortices within the flow, and this problem tends to be particularly acute in regions of the flow where the vorticity is most concentrated - and hence where the need to ensure the accuracy of the simulation is most keenly felt. A particularly pernicious character of these methodologies is that they tend to provide very little indication to the analyst that such errors have taken place, and thus that the representation of the flow is becoming steadily less accurate as the simulation progresses. Although these models undoubtedly have their place in simulating less demanding fluid dynamic problems, and indeed are gaining in popularity in rotorcraft-related applications, the tendency of the output of these models to become steadily less representative of the true solution to the fluid dynamic equations as time progresses makes the class of Lagrangian methodologies a very poor choice for the study at hand.

9.6 Limitations of the present approach

By the very nature of the term, the representation of the physical world within a numerical simulation can never be complete or perfect. Apart from the approximations that always need to be made in constructing the numerical algorithms that represent the behaviour of the fluid, various simplifications and representations of the physical world always need to be introduced - some perforce and others as a matter of good scientific practice. Indeed, a judicious set of choices with regards to which effects to omit and which to retain in any particular simulation can be instrumental in giving the clearest window into the behaviour of the physical system that is being investigated.

Three principal simplifying assumptions were introduced into all the simulations that were conducted as part of the present study. All three have to do with the treatment in the simulations of the ground surface below the aircraft. Firstly, we assumed that the ground plane is smooth, flat and featureless, with no asperities or perturbations that might, for instance, act as triggers for the local de-stabilisation of the flow (and thus potentially to premature destruction of some of the coherent structures in the wake). Indeed, a future study might examine the potential for such features, perhaps even when placed purposefully on the ground, to ameliorate some of the more pernicious characteristics of the outwash at large distances from the vehicle. Secondly, the ground plane was assumed to be infinite in extent in all directions surrounding the helicopter. No effects of ground structures, topography and so forth were included in the simulations. This means that care must be taken when extrapolating to more practical situations where the presence of walls and other enclosures might reflect vorticity back into the flow, or concentrate it, thus possibly amplifying some of the effects observed in this study. Thirdly, the effects of fluid viscosity in stirring up secondary vortical structures on the ground have been neglected entirely. This physics has been implicated in some studies of ground effect[49], especially in the context of small-scale systems, but its omission simplifies the calculations considerably and can be justified on the basis of the aerodynamic scales that are involved. Readers should take care though in extrapolating the work that is presented here to the behaviour of small drones and UAVs where these secondary effects may indeed start to become important.

This particular treatment of the ground has consequences for how the development of the wake below the aircraft is represented with the vehicle in forward flight, and also when the aircraft is subject to wind. The absence of a source of vorticity on the ground leads to these two situations being represented as entirely equivalent cases – groundspeed in the case of forward flight translates directly to airspeed in the presence of wind. This is not entirely representative of the real-world state of affairs, where the presence of viscous shear between the ground and the air leads to the development of an atmospheric boundary layer and a variation of velocity with height within the airflow, when wind is present, that is not there when conditions are calm. Representing the effects of the atmospheric boundary layer is indeed possible within the VTM, and can lead to some very interesting wake dynamics[50], but, on the basis of retaining as much generality as possible, such considerations were omitted entirely from the present study.

Indeed, the properties of the atmospheric boundary layer are strongly dependent on the details of the surrounding topography, including the distance over which the layer has had time to develop (so whether the modelled ground surface is part of an airfield or a section of an elevated helipad, for instance), the properties of the ground surface (for instance, whether the ground is smooth or covered in vegetation) and the effect of nearby obstacles (*e.g.* buildings, fences, and walls) in conditioning the flow. In that vein, if a characterisation of the outwash that will be produced by a specific vehicle in windy conditions at a particular geographic site were to be contemplated, then the arguments that led to the various simplifications that were introduced within this study might fruitfully be re-visited. Also, in the light of these observations, our omission altogether of the atmospheric boundary layer when modelling the system does mean that a modicum of care needs to be taken when extrapolating the forward-flight data that we present to assessing the behaviour of eVTOL aircraft in windy conditions.

10 A taxonomy of eVTOL configurations

It was explicitly not the intent of the present study to provide a critique of the likely properties of any particular set of real-world designs. Rather, the aim was to provide an analysis of the likely characteristics of eVTOL aircraft in sufficiently generic and abstract form, so that, despite the fact that interested parties might perhaps be able to recognise features of their particular designs in the configurations that were indeed simulated, the study would have broader and more foundational applicability to the class of eVTOL aircraft as a whole.

Given the very broad range of configurations which eVTOL aircraft could feasibly adopt, it is essential that some form of ordering principle or comparative basis is adopted at the outset, even if only to catalogue the range of designs that would need to be simulated if the study were to be truly comprehensive. A taxonomy of aircraft configurations thus forms an essential foundation of this study, underpinning our ability to compare and contrast the characteristics of different aircraft designs on a fair and equitable basis. The taxonomy that we have devised is based on the principle of aerodynamic similarity – in other words, on the principle that in changing configuration from one aircraft to another, certain aerodynamic scaling factors should be preserved.

10.1 Disc loading kept constant

In order to isolate the effects of aircraft configuration from the more straightforward effect of disc loading on the properties of its outwash, it follows that the various configurations should be compared on the basis of all having the same disc loading. The most natural way of embodying this invariance is to require that the total propulsor area should not change as the configuration of the aircraft is varied. So, for instance, in comparing two systems A and B, one with N_A rotors, all with equal size, and the other similarly with N_B rotors, then the radii R_A and R_B of the individual propulsors of systems A and B should scale according to

$$\frac{R_A}{R_B} = \sqrt{\frac{N_B}{N_A}} \tag{4}$$

In the ideal situation we would then apply a series of additional constraints so that any differences in outwash behaviour are solely a result of differences between the configurations of the aircraft being compared and are not influenced by essentially extraneous considerations, such as, for instance, changes in the aerodynamic efficiency of its individual propulsors as a result of changes in their size or geometry. Unfortunately, in practice, any means of implementing this ideal is far more easily imagined than applied, and hence a combination of experience and logic needs to be employed to isolate most effectively the role of aircraft configuration in governing the properties of the outwash that any particular vehicle design might produce.

In this vein, and to yield the fairest comparison between the various configurations that were studied, we thus applied two additional constraints – both of which, when implemented together, help to minimise the intrusion of the aerodynamic performance of the propulsors themselves into our ability to isolate the effects of aircraft configuration on the characteristics of the outwash that the vehicle might produce.

10.2 Propulsors have the same geometry throughout

Firstly, in the light of the arguments just made, we require a means of isolating the performance of the propulsor from any changes in its size. This can be done most readily if we begin by assuming the propulsors all to have the same geometric design, up to the inclusion of a scaling factor that can be applied uniformly to all its dimensions if indeed we do wish to change its size. By adopting this approach, the fundamental aerodynamic characteristics of the propulsors will not change, in the sense of its response to its aerodynamic environment remaining the same (up to the dependence on scale effects as embodied in the Reynolds number of the system) no matter what the size of the propulsor. Applying this constraint to the systems that were modelled is a first step towards isolating the effects of configuration from the more direct effects of propulsor design on the properties of the outwash that is created by the vehicle.

Note though that this approach does preclude any consideration in the present study of the potential that the geometry of the propulsors might be optimised to minimise the effects of the outwash that might be created by any particular design. Although the imposition of this “principle of geometric similarity” explicitly suppresses the effects of propulsor design itself on the properties of the vehicle’s outwash, it should also be borne in mind that, in so doing, this approach also precludes detailed comparison of the relative merits of various types of propulsors, for instance ducted propulsors or lift fans compared to propellers or rotors, in perhaps creating a more benign outwash below the vehicle. It could be imagined that one particular design might have advantages in this respect over another, for instance by suppressing (or, more likely, enhancing) the rate at which the vortical structures in its wake de-stabilise as they travel downwards towards, and spread out across, the ground.

10.3 Propulsors have the same aerodynamic performance throughout

A further consideration that must be taken into account when comparing the performance of two different aircraft is that the aerodynamic performance of the propulsors will be influenced by the particular operating conditions at which the aircraft are being flown. A straightforward scaling analysis reveals a range of non-dimensional aerodynamic parameters that need to be matched between the two systems of interest to ensure that the aerodynamic conditions on the propulsors remain the same in all cases – or, in more concrete terms, so that for instance the potential effects on the propulsors’ performance of changes in the spanwise distribution of blade loading, the presence of stall and reverse flow, and so on, are all represented in the same way in each case. The universal bugbear of comparative studies within the VTOL domain is that it can be difficult, in some cases even impossible, to match the entire set of relevant aerodynamic parameters simultaneously if the two systems are not operating at the same flight condition.

With the two systems both in hover, the situation is relatively straightforward, but, in forward or axial flight, we need an appropriate way to relate the speeds relative to the air U_A and U_B of the two systems being compared. Although the classical helicopter approach is to use the (kinematic) advance ratio $\mu = U/(\Omega R)$ to this end, where Ω is the rotational speed of the rotor and R is its radius, this result is not general enough to apply to propulsors of all possible types. The theory of jets in crossflow suggests that a more appropriate similarity parameter to apply to the forward speed of the aircraft, especially when the aerodynamics within the wakes of the propulsors is of primary interest, is the ratio of the speed of the aircraft, U, to the velocity in the jet, V^i (for which Eq. (1) gives an estimate in terms of the disc loading of the system). In other words, if the thrust-weighted advance ratio

$$\mu^* = U/V^i = U/\sqrt{(W/A)/(2\rho)} \tag{5}$$

is the same for the two systems being compared, then the aerodynamics within their wakes will be the same up to a simple geometric scaling factor (so, for example, H/D, where H is the height of the propulsor above the ground, and D is a characteristic dimension – usually taken as the diameter of the propulsor). This expression can be used directly to relate the performance of systems with jet-like propulsors as well as rotor-like propulsors.

The thrust-weighted advance ratio can be written in a form that applies more clearly to rotors by realising that the appropriate scaling factor for the thrust produced by such systems is simply the thrust coefficient, $C_T = T/(\frac{1}{2}\rho A(\Omega R)^2)$. Substituting this definition into Eq. (5) yields an expression for the thrust-weighted advance ratio that is specific to rotor- or propeller-like propulsors:

$$\mu^* = U/V^i = (U/\Omega R)/\sqrt{C_T/2} \tag{6}$$

This expression reveals some of the complications in matching conditions between two systems so that the aerodynamic performance of the propulsors is the same in both cases. As discussed in the previous paragraph, the geometry of the propulsors (including the pitch of the blades in the case of a propeller or rotor) is already assumed to be an invariant. This additional constraint implies that, if aerodynamic equivalence between systems is to be ensured, then the thrust of a propeller-like propulsor must be controlled through some means other than by any mechanism that might vary the geometry of the blades.

Although using the blade pitch to control the thrust is common helicopter practice (and indeed is becoming more prevalent within the eVTOL community as its benefits are realised), a fairly broad spectrum of eVTOL aircraft use the rotational speed Ω of their propellers to similar purpose. This is the approach that we have adopted in the present study, and indeed it allows aerodynamic equivalence to be achieved much more straightforwardly than through any other approach that we could devise. If the rotational speed of the rotors is used to control the thrust that they produce, then, on combining the restrictions that have been introduced so far, it can readily be shown that, when comparing systems A and B, one with N_A rotors, all with equal size, and the other similarly with N_B rotors, the (nominal) rotational speeds Ω_A and Ω_B of the individual propulsors of systems A and B should scale according to

$$\frac{\Omega_A}{\Omega_B} = \sqrt{\frac{N_A}{N_B}} \tag{7}$$

A significant and welcome up-side of adopting this scaling is readily apparent. If the rotational speed of the rotors is scaled according to Eq. (7), then the thrust-weighted advance ratios of the two systems will be the same (assuming that the systems being compared both have the same disc loading) simply if their speeds relative to the air are the same, or, in other words, if $U_A = U_B$. Throughout the comparative studies that were performed as part of the work presented here, we have chosen thus to match the thrust-weighted advance ratio together with the disc loading of the propulsors no matter what their type. We realise though that the equivalent procedure in the case of propulsors that are propeller- or rotor-like is to match their thrust coefficient and to scale their rotational speed according to Eq. (7), and, where appropriate, this more direct methodology was applied.

Using the thrust-weighted advance ratio μ^* rather than the kinematic advance ratio μ to ensure equivalence between any two systems being compared has the additional advantage of allowing direct access to a highly relevant body of previous research, in particular Curtiss's work[11] on classifying the qualitative behaviour of rotor wakes according to their forward speed and height above the ground, to help us frame the outputs of the present study. This advantage will become very apparent in the later sections of this report where we frame the properties of the outwash that is created by complex, multi-rotor eVTOL aircraft in terms of the scaling analysis that we have presented above.

10.4 The result: A taxonomy that is agnostic and complete

The importance of the taxonomy as defined here is that it stands the chance of being able to encapsulate the complete range of configurations into which the propulsors of eVTOL aircraft can be arranged. This property comes about simply through the taxonomy being founded on an essentially geometric argument that if N rotors are selected, then these rotors can be arranged into a discrete set of possible configurations, and if those configurations are then constrained by considerations of aerodynamic similarity, then the range of possible permutations falls naturally into a hierarchical order (see Figure 16). In practical terms, a taxonomy that has these properties has the particular advantage of allowing the study to be elevated above real-world considerations of taste or designer preference, and, most importantly, in avoiding any bias in the study (other than by selection of which configurations to model given the unavoidable conflict between finite resources and the extent of the taxonomy) towards any particular manufacturer or existing design of vehicle. This is not to say that features of certain particular aircraft of practical interest cannot be identified in the geometric characteristics of any of the configurations that were modelled – indeed, the taxonomy would be self-defeating, and have very little real-world relevance, if this were not the case!

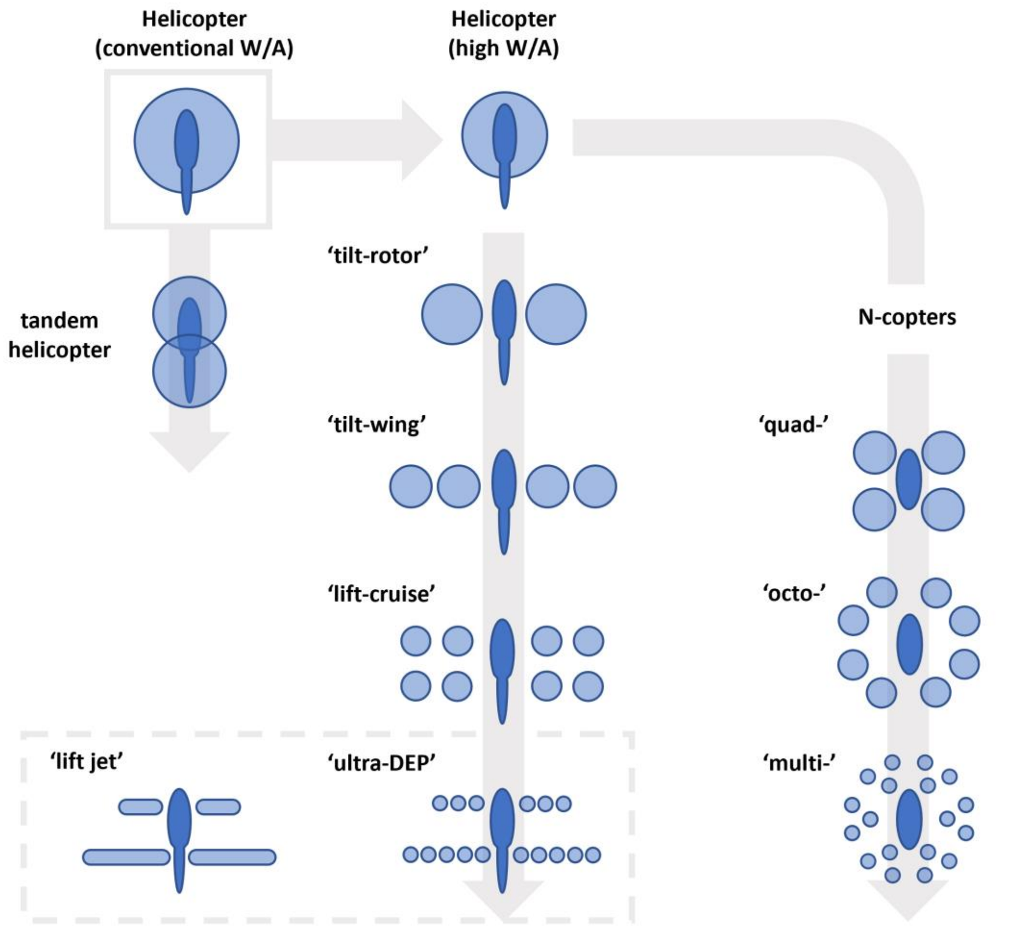


Figure 16: A taxonomy of eVTOL aircraft that is based on number of rotors but constrained by considerations of aerodynamic similarity.

10.5 Implementing the Taxonomy

Given constraints on time, only a limited number of configurations could be investigated in detail during the course of the present study. The configurations that we were able to study were selected to give fairly judicious coverage of the range of configurations that are currently under development within the eVTOL community. Again, we reinforce the point that the intent was not to favour or to denigrate any particular manufacturer's product with our particular choice, and, indeed, in time we hope to cover the spectrum of possible aircraft configurations in greater breadth.

Each of the configurations that were selected for study was embodied as a notional aircraft design, which could then be "flown" within the computational environment that we used to simulate its aerodynamics. In this way, the properties of the aircraft's outwash could be investigated in detail over a range of representative flight conditions. The set of notional aircraft designs that emerged from this process are shown in Figure 17 and Figure 18.

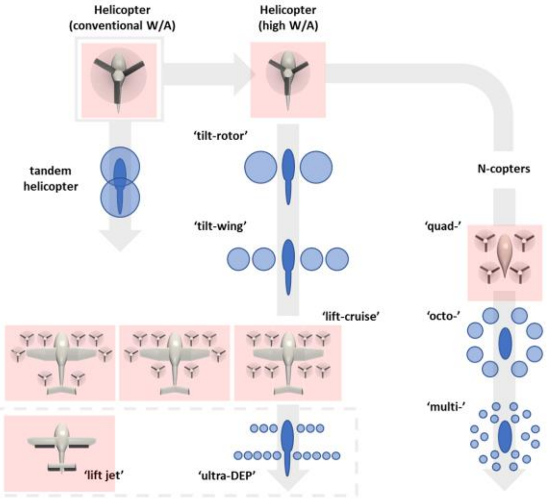


Figure 17: A small range of configurations (marked in red and represented as notional aircraft designs) were drawn from the taxonomy so that their aerodynamic characteristics could be investigated in detail.

The first design embodies the simple quad-copter configuration, and has a simple pod-like fuselage with four relatively large rotors arranged in a rectangular layout. The rear rotors are mounted somewhat closer together, and are located higher on the sides of the fuselage than the front rotors. This was done specifically to provoke aerodynamic behaviour within the outwash field that would not necessarily have emerged if the fore-aft geometric symmetry of the vehicle had not been broken.

The second design embodies one possible version of the "lift-cruise" configuration, and consists of eight rotors mounted relatively high above the ground, in line with a gull wing that was given moderate aspect ratio and taper and attached to the top of the fuselage. The design was given an H-tail "bomber" empennage and a "teardrop and boom" fuselage in order to allow the simulations to represent more faithfully some typical aspects of real-world eVTOL aircraft – as well as indeed to allow the aerodynamic interactions between these components, the ground and the propulsors to be explored. Three different permutations of this configuration were examined, as shown in Figure 18. The aircraft in its basic configuration had its rotors arranged symmetrically fore and aft of the wing in a rectangular layout. A second permutation had the two outermost rotors behind the wing shifted forwards and outboard so as to break the fore-aft symmetry of the basic configuration, and a third permutation was derived directly from this by shifting the remaining rotors immediately behind the wing further aft in order to explore the effects of rotor separation on the directionality of the flow within the outwash.

The propulsors of all these systems were modelled to be propeller- or rotor-like in their aerodynamic character. What this means in practical terms is that the aerodynamics of each propulsor was modelled as though all the aerodynamic forces created by the device were produced by a series of spinning blades oriented at an angle of incidence to the local flow. The structure of the wake of such a device is then comprised of the sheets of vorticity that are produced by each of the blades - these sheets then interleaving in helical fashion as they pass into the flow below the plane of the rotor.

The design of propulsor that was adopted was based on fairly conservative eVTOL design practice, each rotor having three blades with moderate aspect ratio and twist. The rotors could thus be expected to have aerodynamic performance that is broadly representative of current eVTOL practice. No attempt was made to accommodate more esoteric geometrical considerations such as might be required, for instance, to minimise rotor noise or to optimise for maximum figure of merit at one or another specific operating condition. The consequence of such optimisation for the properties of the outwash that is produced by these vehicles remains an interesting, but open question.

Forms of propulsor other than propellers and rotors are entirely feasible - and indeed are of considerable interest in terms of their utility as thrust producing devices for eVTOL aircraft. To explore the characteristics of the outwash that might be generated by an aircraft with a very different type of propulsor than the propellers or rotors that are usually associated with electric propulsion, an additional aircraft design was modelled in which the rotor-like propulsors of the configurations already described were substituted for jet-like ducts. In this "lift-jet" design, shown at bottom right in Figure 18, features representing the aerodynamic characteristics of propulsive ducts were mounted along the trailing edge of each wing, and two shorter such ducts were located just behind the tailplane of the aircraft.

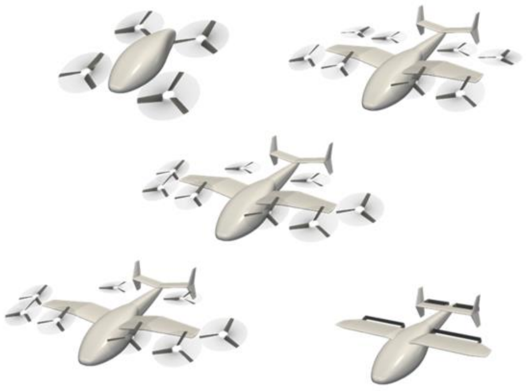


Figure 18: Notional aircraft designs that embody various configurations within the taxonomy developed earlier. Top left: "quad-rotor". Bottom right: "lift jet", and, diagonally across the centre, three variations on the eight-rotor "lift-cruise" configuration.

In the simulations of this design, the aerodynamic forces were created by attaching an annulus of vorticity to the exit of each jet. In this arrangement, the wake below each propulsor, in consisting solely of a tubular sheet of vorticity extending downwards into the flow below the duct, is also very much simpler in structure than the wake that is created by a propeller or rotor.

A note on the level of detail embodied in the computational representations of the aircraft geometries is potentially helpful here, given that to some eyes our renditions may appear to be somewhat crude and stylised through their omission of detailed features such as rotor hubs and mountings, undercarriages, and so on. In fact, we consider the abstraction that results from our approach to be a strength of the analysis in allowing a broad-brush characterisation of the outwash that might be created by each generic type of aircraft that is unencumbered by quibbles over the effects on the aerodynamics of the system that might result from the inclusion (or not) of this additional detail. Indeed, the level of geometric representation that we have adopted is entirely consistent with our intent to provide an overview of the general characteristics of the outwash field that is created by the eVTOL aircraft that we have been able to simulate during the course of this study, particularly when these have been defined from the outset to represent generic and abstract members of the broader class of vehicle.

Despite this observation, we acknowledge that it has been shown on multiple occasions throughout the history of rotorcraft flight-dynamic testing that relatively small additions to a real aircraft's geometry, for instance in the form of strakes or fillets placed judiciously on its airframe, can have a disproportionately large, and generally positive effect on the character of the aerodynamic environment that the vehicle creates for itself in its own surroundings. We acknowledge the possibility here that small changes to our modelled geometries may indeed have large effects on the outwash that they produce, and indeed we encourage further study along these lines - the reward potentially being a deeper understanding of the means available to designers in mitigating some of the effects of outwash that we have observed.

10.6 Reference configurations

The ground that could be covered in the time available to complete this study was relatively limited compared to the size of the configuration space that is available to the designers of eVTOL aircraft. We thus needed to concentrate our study on parts of the design space which seemed most salient to the possibility that the outwash that might be created by the vehicle would have real-world consequences for the operational safety of this type of aircraft. In this vein, we have focused in quantitative terms on determining the likely strengths of the outwash of the type of aircraft that would be found in "cluster C" of Figure 13 relative to comparable helicopters. In qualitative terms, however, our exploration of the shape and character of the outwash that is produced by aircraft with various different configurations will be much more broadly applicable.

To aid in quantification of the likely magnitude of the velocities in the outwash field of any of the particular aircraft that were investigated as part of this study, particularly when scaled to have size and weight that is representative of current eVTOL practice, we have defined two additional aircraft configurations to act as suitable baselines against which to compare the properties of our representative eVTOL aircraft designs.

The embodiments of these configurations for the purposes of numerical simulation are shown in Figure 19. Both of these designs are helicopter-like in consisting of a single main rotor mounted above a "teardrop and boom" type fuselage. The first design was given a rotor with the same area as the overall disc area of the eVTOL aircraft defined in the previous section. This design (if compared on the basis of equal weight) has the same disc loading as the eVTOL aircraft defined in the previous section and allows direct comparison of the configurational effects on the outwash that arise between helicopter- and eVTOL-like vehicles, unencumbered by the complications that are introduced by differences in the disc loading between the systems that are being compared.

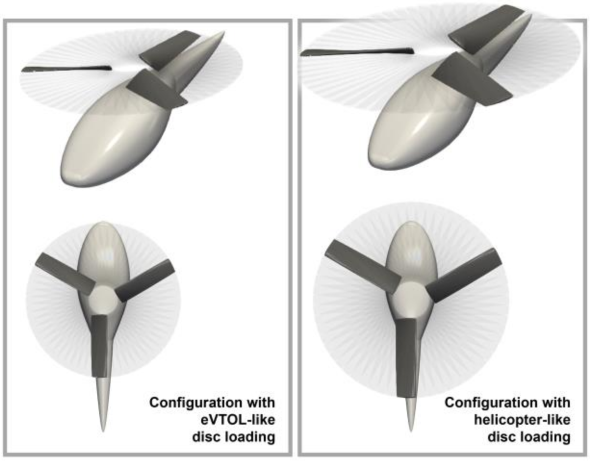


Figure 19: Helicopter-like reference configurations. The configuration at left has eVTOL-like disc loading whereas the configuration at right, given its bigger rotor, has helicopter-like disc loading.

The second design adopts the converse approach in having the radius of its rotor *increased* by 26% so that the eVTOL designs, for the same weight of aircraft, will all have 60% greater disc loading (and thus produce about 26% greater downwash velocity) than this vehicle. This particular increment in disc loading was chosen to represent the properties of the aircraft in "cluster C" of Figure 13 in terms of their disc loading compared to helicopters with similar weight. The somewhat unworldly appearance of the rotors of both these reference designs is a consequence of extending the scaling arguments derived in Section 8 to allow the outwash properties of these "helicopters" to be matched on equal terms with those of the eVTOL designs that were described in the previous section.

11 Supporting Analysis

Some initial observations regarding the structure of the wake that forms in the air below a typical rotor are in order. These observations are particularly general but serve to frame and unify the more detailed analysis of the aerodynamics of eVTOL aircraft that is presented later. We first try to understand the structure of the wake that is created beneath an isolated propulsor in free air. The situation is then complicated by introducing the effects of the ground on the structure of the wake of the propulsor. Finally, the physics of the interaction between the wakes that are produced by a pair of rotors operating close to the ground is considered. Understanding the physics of these three simplified cases will help later in our interpretation of the more complex aerodynamic environment that is produced by multi-rotor vehicles, and potentially where the addition of wings, tails and fuselages adds further to the complexity of the flow.

We focus here on the properties and behaviour of the wakes that are created by propeller- and rotor-like propulsors in the process of generating lift, but, given our interest too in other forms of propulsion, where appropriate we attempt to explain how our inferences transfer to the structure of the efflux from propulsors that are jet-like in character.

11.1 Behaviour of the propulsor wake

Figure 20 shows the conceptualisation of the wake below a propulsor that is provided by simple considerations of momentum transfer to the fluid as it passes through a propeller- or rotor-like device[51]. A column of air is captured by the propulsor, and, as a result of the pressure differential that is created between the upper and lower surfaces of the propulsor in the process of generating lift, the flow within this column of air accelerates. If the system is in hover, then far above the rotor, the pressure in the flow is the same as in the surroundings and the velocity of the flow in the column is zero.

The maximum pressure in the flow is attained immediately below the rotor, and the velocity through the system at this point is the induced velocity V^i - as given by Eq. (1). As the pressure within the column relaxes back to atmospheric conditions below the rotor, the flow continues to accelerate, reaching a maximum velocity of $2V^i$ far downstream of the system. Finally, mass conservation within the column of air requires its cross-sectional area to change in response to changes in the velocity of the flow. This means that if the column of air has area A at the rotor, then far downstream it will contract to have area $A/2$.

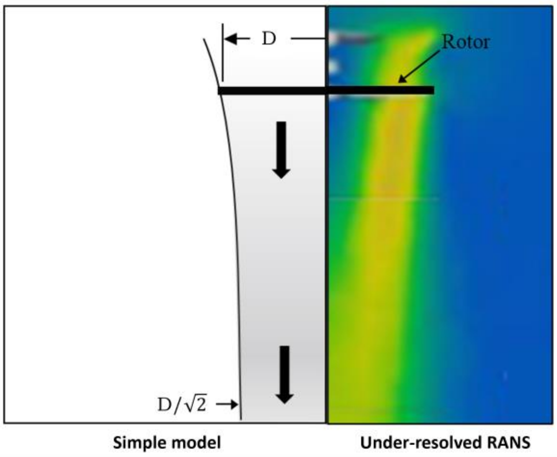


Figure 20: (left) simple momentum model of the structure of the rotor wake. RANS methodologies[41] (right), especially when the flow is under-resolved, tend to reproduce rather well the flaws that are predicted by the simple momentum model, but for the wrong reasons.

This simple momentum-based conceptualisation of the downwash field allows a basic understanding of how the properties of the flow are affected by the simple action of the propulsor in producing lift, and indeed this model forms the foundation of many simple analyses for the behaviour of rotorcraft under a wide variety of circumstances. Ferguson's influential analysis[1] of the behaviour of the outwash below hovering helicopters, described in some detail earlier, is largely momentum-based, as is the majority of the early methodologies that were used in the jet-lift community to model the interaction of the flows that are created by multiple propulsors when they impinge upon the ground[9]. Interestingly, many numerical methods that are based on the velocity-pressure-density formulation of the governing equations tend to produce solutions that are very similar to those given by this simple approach, particularly when the grids that are employed to support the calculation are too coarse to resolve any of the finer detail in the flow (see Figure 20). Although any sense of security in the predictions of these methods as a result of this agreement is largely unwarranted, this equivalence is not entirely unexpected. Indeed, to have any basis in physical reality at all, even the simplest numerical methodologies should be capable of resolving, in broad terms at least, the momentum transfers within the fluid that are required to create a suitably-accelerated column of air through a thrust-producing rotor.

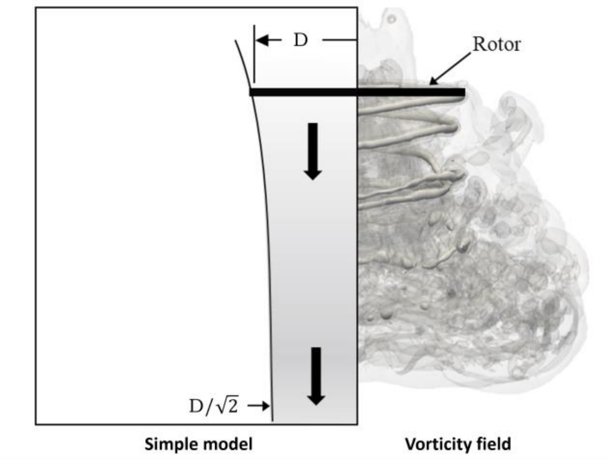


Figure 22: simple momentum model of the structure of the rotor wake at left, compared to a visualisation of the internal vortical structure of the wake obtained using the VTM. The flow within the wake is far more complex than the simple models would suggest.

Analysis of the flow through the propulsor at the level of simple momentum transfer omits much of the fluid mechanics that is relevant to understanding how the outwash field is created, however, and indeed the theory, although simple to apply in simple situations, is founded on a number of assumptions regarding the topology of the flow which make it very difficult to understand how certain key properties of the outwash can arise. This turns out to be particularly the case where the flow over the ground is the consequence of the interaction of the wakes that are created by multiple rotors. Given the prime relevance of this particular situation to the present study, we need a more sophisticated view of the fluid dynamics in the wake of a hovering rotor.

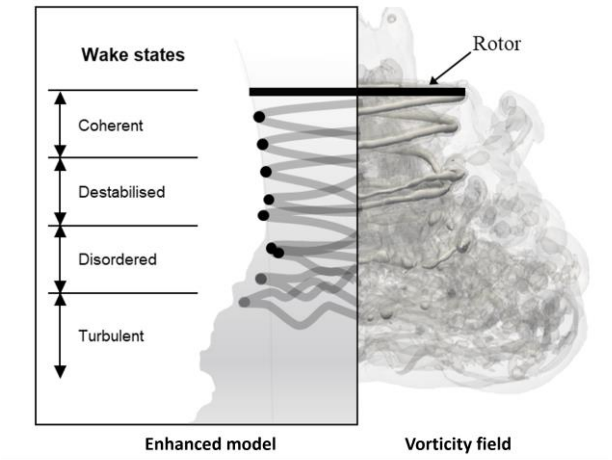


Figure 21: conceptual model showing the evolution of the structure within the rotor wake through a series of states as distance away from the propulsor is increased. This evolution has important consequences for the structure of the outwash field.

11.2 How is the downwash field created?

A snapshot of the vorticity distribution within the wake below a hovering rotor, obtained from a numerical simulation using the Vorticity Transport Model (VTM), is compared in Figure 22 to the predictions of the simple momentum model. The VTM provides a much clearer and more accurate depiction of the structure of the wake as it evolves below the rotor.

In the process of creating lift, each blade of the rotor creates a sheet of vorticity that trails behind it. For most rotor designs, the loading along the length of the blades tends to vary most quickly near the tips, causing a concentration of vorticity (generally identified as the “tip vortex” of the blade) close to the outer margin of the sheet. The combination of the blade’s circular motion around the hub of the rotor, and any forward motion of the rotor through the air, together with the downwash velocity (the existence of which is intimately tied to the presence of the vorticity in the wake in the first place) causes the vortex sheets that are created behind the blades to adopt a corkscrew-like, helical geometry as they are convected down and away into the flow below the rotor to form its wake. The helical structure of the tip vortices is clearly visible in Figure 22, especially in the wake just below the rotor.

The dynamics of these helical structures is inherently unstable, however. Any small perturbations to their shape (and such perturbations, whatever their origin, are always present) are amplified and enlarged, so that, as these features descend into the flow below the rotor, their structure becomes increasingly tangled and knotted. The most important forms of instability[12,52,53] to which a helical vortex is prone are the so-called ‘leap-frog’ instability, where successive loops within the helical vortex structure exchange their position as time progresses (such an exchange can be seen in Figure 22 to be taking place at about one radius below the rotor), and the ‘short wavelength’ mode where crenellations begin to appear along the length of an individual vortex, and the subsequent fluid dynamics eventually leads to its rapid dissolution as these perturbations to its originally smooth geometry grow in amplitude. The effects of this mode of instability are most clearly visible during the last stages of coherence of the wake shown in Figure 22, and indeed are even more clearly visible in the images of the full-scale helicopter wake shown earlier in Figure 3.

The importance of these instabilities is that they cause the wake below the propulsor to transition through a series of states as the distance below the rotor is increased. The conceptualization of the structure of the wake that results from this more sophisticated view of its internal dynamics is shown in schematic form in Figure 21. Closest to the rotor, the wake consists of vorticity that is highly structured and coherent. Further away from the rotor, the wake starts to lose some of this coherence as the natural instabilities start to have an effect. Indeed, the wake becomes increasingly more disordered as the distance away from the rotor is increased. The long-term action of the inherent instability of the vortical system is to destroy the coherence of the older elements of the wake entirely and to dissolve any remaining structure to form a cloud of small-scale, highly tangled vortical filaments that ever more closely resembles a state of turbulence as the distance below the rotor continues to increase. Indeed, the final effects of the instability of the system of vortices is to produce the cloud of vorticity in the far-field below the rotor that is clearly visible in Figure 21. This cloud is very inert and slow-moving, and, indeed, if the VTM simulations that were used to produce the image of the wake shown in Figure 21 were to be left to run for much longer, then the cloud would continue to grow - eventually extending to considerable distances in all directions from the rotor.

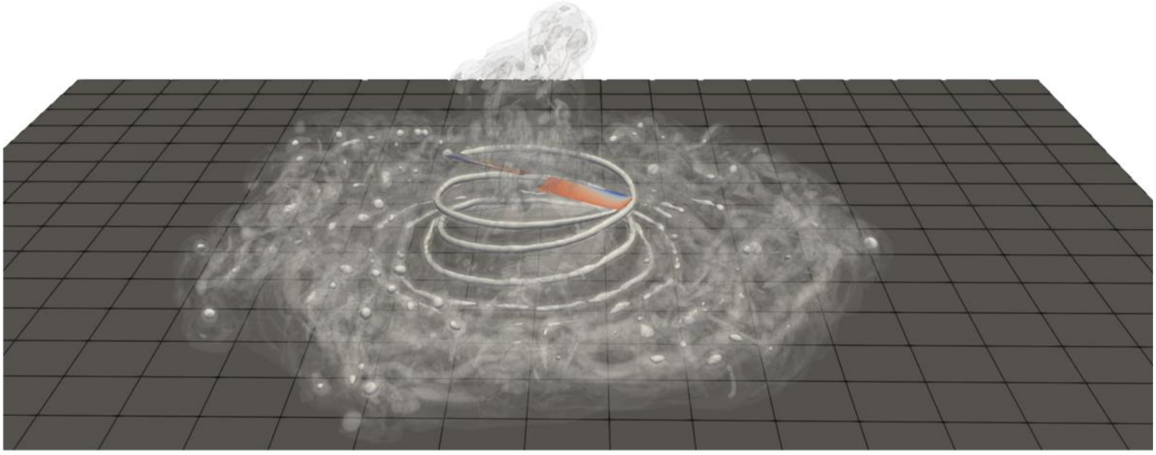


Figure 23: VTM-generated visualisation of the flow in the outwash below an isolated, two-bladed rotor hovering above the ground. The outwash has significantly more structure than is suggested by the simpler aerodynamic models.

The effect of the unstable dynamics of discrete vortices is less marked in the evolution of the efflux of a jet-like propulsor. This is principally because the wake of the jet at its point of creation has less structure than that of a propeller-like device. Instead of having the discrete sheets of vorticity that are created by each of the blades of the rotor, the boundary of the wake of the jet near its origin (discounting the presence of features within the jet, such as the presence of vanes and crenellations which might create additional structure) consists of a relatively smooth, cylindrical sheet of vorticity. This so-called “shear layer” is subject to its own natural fluid dynamic instability, which in this case causes the vorticity in the cylindrical sheet to clump up, creating a series of characteristically-spaced loop-like structures in the wake which become ever more pronounced with increasing distance below the propulsor. Eventually the analogues of the leapfrog and short-wavelength instabilities take over, but the net effect, at least for jet-like propulsors that are being operated at rotor-like disc loadings, is for the coherence of the wake below the jet to persist to greater distances below the propulsor than is usually the case with rotor-like propulsors. This picture of the evolution of the wake below a jet-like propulsor can be complicated considerably if the efflux from the jet is not perfectly round. Indeed, some of the results presented later will show just how three-dimensional and non-linear the dynamics of the vorticity in non-circular jets can become.

11.3 What happens when downwash turns to outwash?

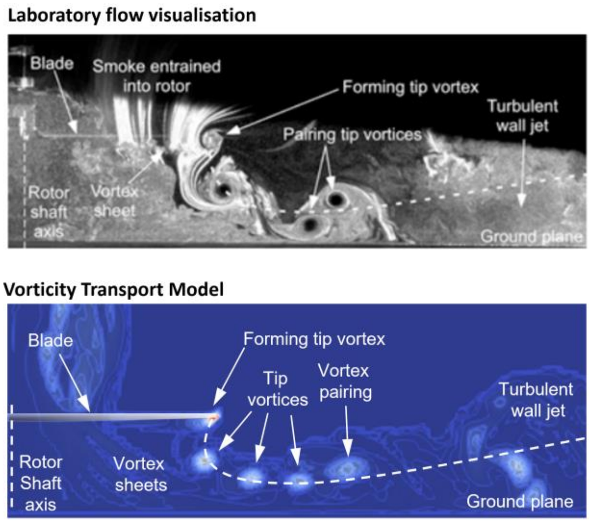
The importance of this more nuanced view of the internal structure within the wake becomes apparent when trying to understand what happens when the wake below the propulsor makes contact, and subsequently interacts with the ground. Figure 23 gives an overall picture, generated using the VTM, of what happens when the wake below a simple two-bladed rotor spreads out across the ground to create an outwash. What should be most clearly apparent is that the flow in the outwash is markedly inhomogeneous in its structure – the actual state of affairs being in strong contrast to the smooth, jet-like flow that is envisaged by simple conceptualisations of the salient fluid dynamics.

Figure 24 and Figure 25 present a more detailed view of the changes in the structure of the vorticity within the outwash that take place as the flow spreads out across the ground. In these two figures, small-scale experimental data[7] is compared against the predictions of the VTM to reveal some of the detail of the interaction of the wake of a rotor-like propulsor with the ground. Indeed, the very close qualitative match between the evolution of the structure in both experimental and numerical cases serves as good verification of the quality of both the numerical and the model-scale characterisations of the flow.

More importantly, it should be readily apparent to the reader that the conceptualisation of the structure within the wake that was introduced in the previous section can be extended rather straightforwardly to the situation when a ground plane is present. Indeed, the transition of the wake from having a relatively ordered structure near the rotor, followed by its disorganization and loss of coherence to produce a turbulence-like flow at some distance out across the ground plane, is particularly evident in this set of images.

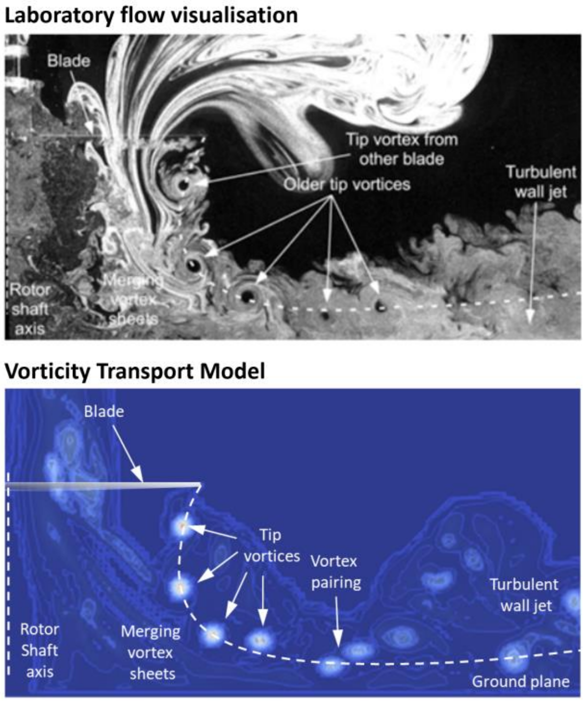
Figure 24 and Figure 25, taken together, suggest very strongly that the form of the propulsor's interaction with the ground is affected significantly by the distance of the propulsor above the ground when the interaction takes place. The interrelationship between the height of the rotor above the ground and the progression of the structure of the flow in the outwash through a set of characteristic modes is summarised in schematic fashion in Figure 26, where the analysis that was presented in Figure 21 for the propulsor in free air is extended to the situation where a ground plane is present.

With the rotor close enough to the ground, the fluid dynamic instabilities within the wake might not necessarily have had sufficient time to disrupt the structure of the vorticity before elements of the wake that are still reasonably coherent make contact with the solid surface below the propulsor. The disordering process is thus still somewhat incomplete at the point where the wake makes contact with the ground. In this case, the disordering of the vortical structures continues to run its course as the wake spreads out across the ground. Under these circumstances, the flow within the outwash can be characterised for quite some


Laboratory flow visualisation

Vorticity Transport Model

Figure 24: Laboratory flow visualisation[7] (top) and VTM simulation (bottom) of the outwash beneath a rotor hovering at H=0.25D above the ground. Both representations of the flow show the characteristic progression of the flow in the outwash through a series of states as distance out across the ground is increased. This progression is mediated by the natural instability of the vortical structures within the rotor wake.


Laboratory flow visualisation

Vorticity Transport Model

Figure 25: Laboratory flow visualisation[7] (top) and VTM simulation (bottom) of the outwash beneath a rotor hovering at H=0.50D above the ground. With the rotor higher above the ground than in the previous figure, the flow in the outwash is significantly more disordered.

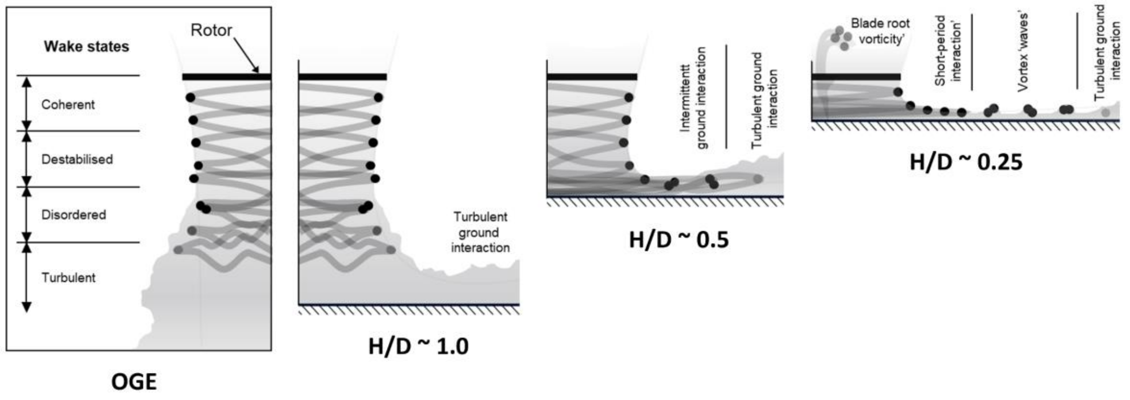


Figure 26: Schematic explaining how the changes in structure of the outwash with the rotor at various heights above the ground can be related back to the effects of the natural instability of its constituent vortices.

distance out across the ground plane by the presence of discrete, coherent vortical structures that are embedded in the flow just above the ground. Most importantly in this case, the leapfrog instability, instead of destroying the coherent, individual structures that remain within the outwash field, can act instead to collect and coagulate these into larger, more powerful features in the flow. These concentrated vortices are then able to propagate with increased intensity and speed out and away across the ground.

As the height of the rotor above the ground is increased, the action of the instabilities within the wake is to cause the structures that eventually impinge on the solid surface below the rotor to become less and less coherent. The point is eventually reached, with the rotor high enough above the ground, where the flow within the wake is essentially turbulent by the time that it reaches the ground. In this case, the outwash itself contains very little internal structure, but instead spreads out across the ground as a deep, chaotic and billowy volume that contains the tangled, weak remnants of the vortical structures that originated at the rotor blades.

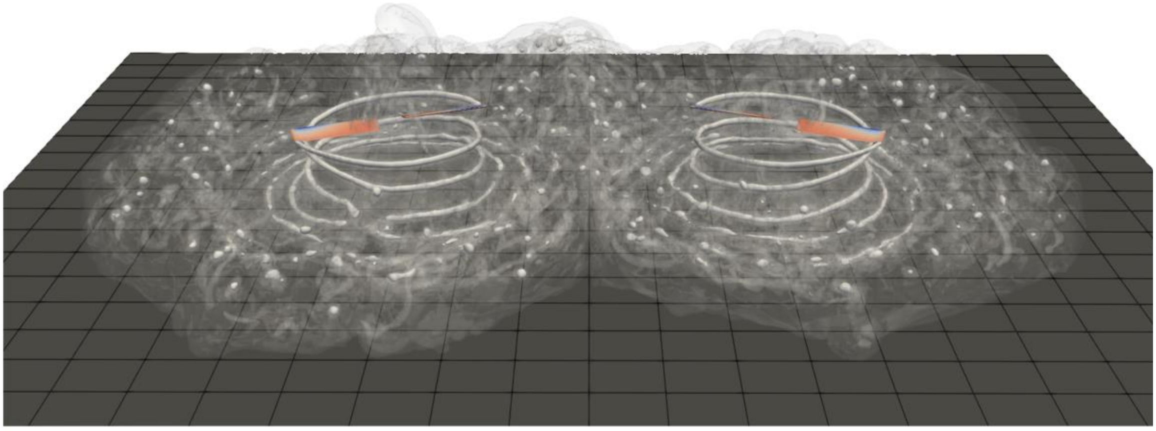


Figure 27: VTM-generated visualisation of the flow in the outwash below between two, counter-rotating, two-bladed rotors hovering above the ground. The fountain flow that is created at the confluence of the wakes of the two rotors is clearly visible.

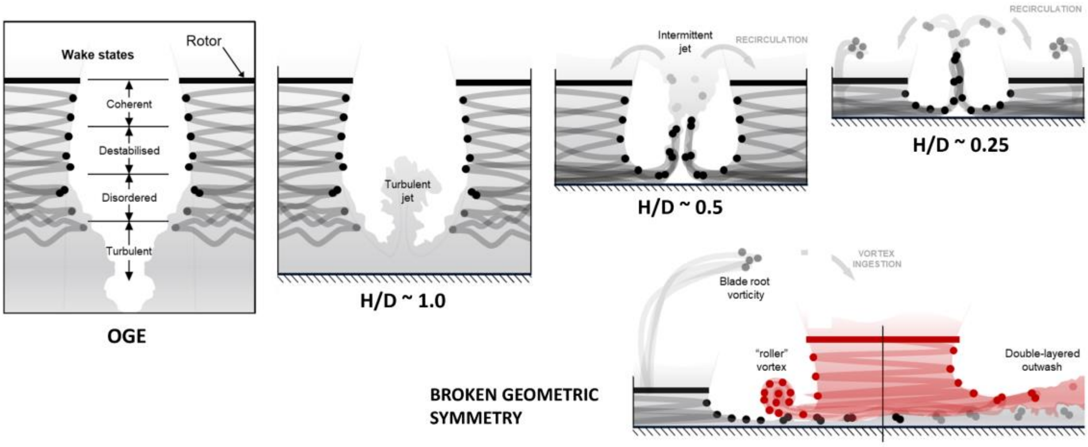


Figure 28: Schematic explaining how the changes in structure of the outwash, with the rotors at various heights above the ground, can be related back to the effects of the natural instability of their constituent vortices for the case where the outwash fields that are created by two different rotors interact. The diagram at bottom right shows one particular situation that is quite commonly observed when the geometric symmetry of the system is broken.

A crucial point to emphasize in the present context is that the relevant aerodynamic scaling parameter is the rotor diameter D. What this means is that a small rotor might produce a turbulent outwash when operating at the same height above the ground at which a larger rotor might produce a much more coherent flow outwards across the ground. This effect of rotor size on the type of outwash that is produced by the propulsor will be seen clearly in some of the examples that follow.

11.4 What happens when the outwash from several rotors interacts?

Figure 27 shows some of the details of the structure in the flow as the wake from a pair of rotors spreads out across the ground and interacts. Where the wakes come into contact, the outwash is turned vertically to produce an upwards-directed flow between the rotors. This characteristic feature of the interaction between two or more rotors in the presence of the ground is usually termed a "fountain flow", and, if present, its effects on the aerodynamics of the parent aircraft when operating near to the ground can be profound[22,23].

If strong enough, these fountain flows can lift debris from the ground, where it might subsequently impact with the airframe or be re-ingested through the rotors. The flow can impinge on parts of the airframe and augment the lift that is produced by the aircraft when operating close to the ground, but the unsteadiness of the flow in the fountain can also lead to buffeting of the airframe and to very non-linear behaviour of the aircraft in response to control inputs. Indeed, and as shall be shown later in this report, the presence of these fountain flows at the confluence of the downwash fields that are produced by their various propulsors plays a strong role in defining the aerodynamic characteristics of eVTOL aircraft when operating close to the ground.

11.4.1 Fountain flows

The character of the flow within the fountain is again a function of the height of the rotors above the ground, as well as of the lateral separation between their axes of rotation. This relationship is summarised in schematic form in Figure 28. As before, the relevant aerodynamic scaling parameter is the rotor diameter, D, implying that larger rotors generate the same qualitative effects at larger separations from each other and at greater distances from the ground when compared to smaller rotors. Again, although a momentum-based representation of the flow is useful in forming our basic concept of the fountain as the result of the confluence of two opposing streams of air midway between

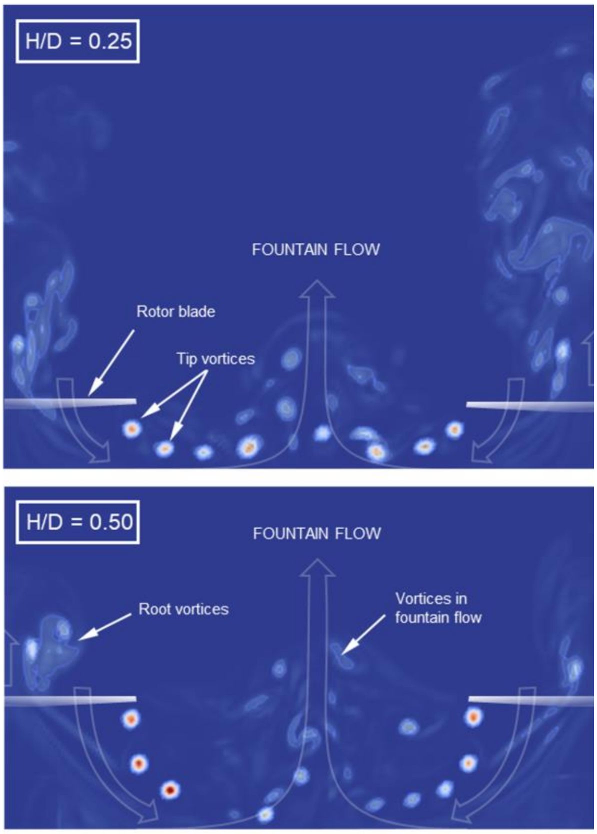


Figure 29: VTM visualisation of the flow when the outwash fields from two similar rotors interact. At the intersection of the outwash fields, the flow is turned upwards to produce what is called a 'fountain flow'. The structure within this fountain flow depends on the height of interacting rotors above the ground and the distance between them.

the rotors, a representation of the flow field in terms of the structure of its vorticity yields considerably more insight. As illustrated in Figure 28, and as supported by the VTM-generated visualisations in Figure 29 of the flow on a cross-section containing the axes of the two opposing rotors shown in Figure 27 when operating at two different heights above the ground, it is clear that the structure of the flow within the fountain changes from having a considerable degree of coherence when the interacting rotors are close to the ground or are closely spaced, but that, as the separation between the rotors or their height above the ground is increased, the flow within the fountain becomes increasingly more turbulent in character. As will be seen in the examples presented later, this change in character has profound consequences for the way in which the overall aerodynamic behaviour of an aircraft varies as its height and speed above the ground is changed. As will be seen later too, the outwash from multiple, jet-like propulsors behaves in very similar fashion to that of propeller- or rotor-like propulsors.

The schematic at bottom right in Figure 28 serves to remind us that up to now we have only considered the somewhat overly-symmetric situation where both interacting rotors are level with the ground, produce the same thrust, and indeed are both at the same height above the ground. If any one of these symmetries is broken, then the resultant wake structure is much more complex. The schematic represents one rather interesting situation that we have observed, where the wake from the lower of a pair of rotors is able to undercut that of a second, higher rotor, resulting in a thickened, highly turbulent, layered outwash to the one side of the system.

11.4.2 Jet flows

A very different kind of symmetry-breaking can take place directly within the flow as a result of the action of the fluid dynamic instabilities described earlier. In this case, small perturbations to an otherwise perfectly-symmetric flow are amplified to the point where the geometry of the flow eventually bears very little resemblance to its original form. This form of symmetry-breaking is ubiquitous in the flows that are created by multi-rotor aircraft when interacting with the ground, but one of the most interesting manifestations of this phenomenon can be seen in the way that the flow along the confluence of the wakes of two or more rotors can concentrate to form a highly-unsteady, jet-like structure out along the ground plane. These "ground jets" are the consequence of the formation of secondary, hairpin-like vortical structures within the outwash field, and indeed it seems that much of the potential for eVTOL aircraft to inflict damage on their surroundings can be attributed to the presence of these flows out along certain relatively well-localised axes. Indeed, our calculations suggest that some multi-rotor aircraft, when operating at low altitude above the ground, are capable of generating a whole series of these jets around the periphery of their outwash field, and that the azimuthal location of these jets is dependent on the configuration of the aircraft and, indeed, on its height above the ground. The jets also appear to be subject in some cases to quite considerable meandering of their direction over time, albeit usually within a relatively constrained range of azimuths, rendering their behaviour a little less predictable than might be imagined.

To explain how these ground jets come about, Figure 30 shows another VTM simulation of two rotors when operating at low altitude above the ground. The figure shows the formation of a sequence of hairpin-shaped structures at the confluence of the wakes from the two rotors – these structures accelerate outwards along the line of confluence of the wakes and are eventually ejected into the flow as a succession of concentrated vortical "waves" or "bullets".

The characteristic hairpin-like shape of these ejected vortices is a result of the mutual interaction between the vorticity on both sides of the line of confluence of the wakes - the particular form of the interaction within the junction between the vorticity on the ground plane and within the fountain flow acting to re-orient and re-shape successive elements of the vorticity field into a train of long-lasting, coherent structures.

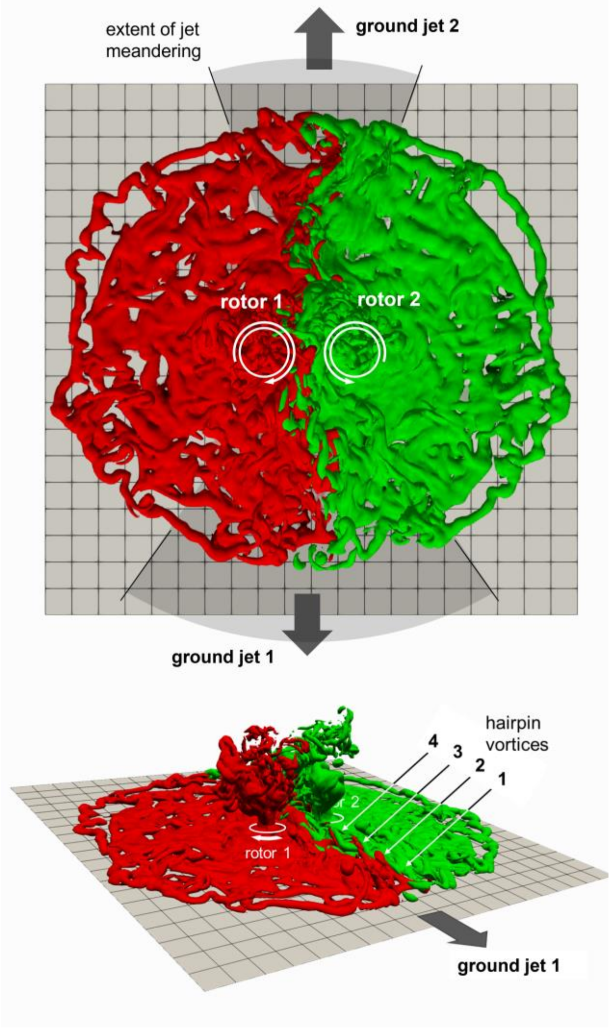


Figure 30: VTM simulation of the aerodynamic interaction between two counter-rotating rotors hovering just above the ground, showing the formation of a ground jet along the confluence of their wakes.

The shape of these structures makes them particularly effective in being able to self-propel at high speed out into the flow surrounding the vehicle. The supply of these vortex 'bullets' is, of course, constantly replenished from the vorticity that is produced by the rotors, and this constancy of supply allows the procession of these individual structures to manifest as a jet-like feature within the outwash field between the rotors. Because the internal structure of these jets consists of a series of these individual, compact vortical structures - all progressing out into the flow in quick succession behind each other - the flow within these jets would be perceived by any observer on the ground as being highly unsteady.

An interesting effect of rotor rotation can be observed in the formation of these jet-like trains of vorticity. In the particular simulation shown in Figure 30, the rotors were set to counter-rotate. It is important to remember that the vortices propagating outwards across the ground plane are essentially helical in structure (rather than circular, for instance). The helical nature of these vortices tends, by providing a slightly increased component of vorticity transverse to the direction of travel of the jet on one side of the pair of rotors compared to the other, to favour the formation of a stronger jet out to the side of the rotor towards which the blades between the rotors are moving outwards. Interestingly, this observation is consistent with data that has been gathered for some tandem-rotor helicopters[17], where it is often the case that the outwash to one side of the aircraft is significantly stronger than the flow out to the other.

11.5 The wake in forward flight

Little attention has been paid so far to the structure of the outwash that is produced by a multi-rotor system in forward flight. A guide as to what to expect is provided by the work of Curtiss[11], who showed experimentally that the structure of the wake of an isolated rotor would undergo a transition through a succession of stable states, or modes, as the forward speed of the propulsor or the height of the system above the ground were varied. Curtiss's 'state diagram' is reproduced in Figure 31, augmented by incorporating some additional structure as revealed by more recent numerical simulations[5]. The reason for plotting the diagram "upside down" compared to its usual presentation will become apparent shortly.

Essentially, as the forward speed of the system is increased with the rotor at a given height above the ground, the outwash field undergoes a sequence of changes in structure. In terms of our vortex-based description of the flow, the effect of forward velocity is to retard the progression of the vortices in the outwash upstream of the propulsor. At the lowest forward flight speeds, and with the rotor fairly close to the ground, the resultant coalescence of vorticity just upwind of the rotor can cause the flow to recirculate through the front of the rotor disc. At higher forward speeds, or with the rotor somewhat higher above the ground, the vorticity upstream of the system compacts to form a concentrated, bow-shaped "ground vortex" located just above the ground.

This structure generally has its apex located just behind the leading edge of the rotor disc, but, as the forward speed of the rotor is increased further, the vortex moves ever further backwards underneath the system. The arms of this vortex generally extend as coherent, arc-like features for quite some distance out into the flow on either side of the rotor before succumbing to the instabilities that by now should be realised are a natural and pervasive feature of the outwash.

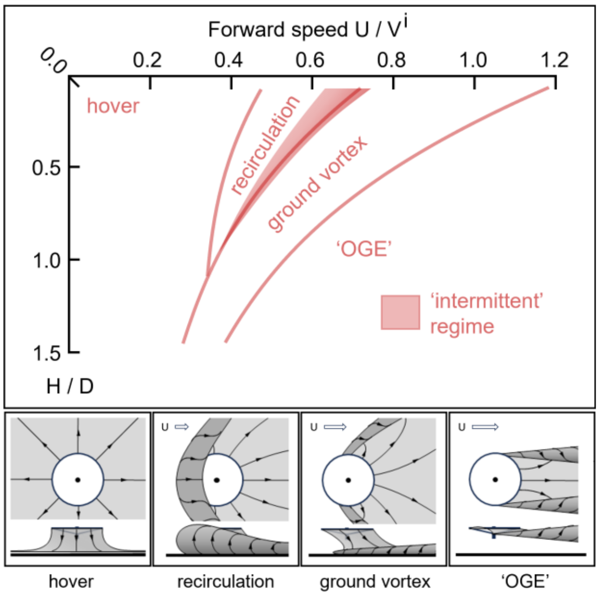


Figure 31: An amplified version of Curtiss's original phase diagram[11] showing the progression of the outwash through a series of states as the speed and height of the rotor above the ground is varied. The schematics at bottom illustrate the morphology of the outwash field in each different state.

At a critical forward flight speed, the entire structure of the wake detaches from the ground, the ground vortex is swept away into the flow downwind of the rotor, and the wake changes from its cylindrical, hover-like morphology into a more flattened, tubular structure that is itself skewed back into the flow behind the rotor.

At even higher forward flight speeds, the wake of the rotor becomes quite aeroplane-like in appearance, and consists, in broad terms, of two large counter-rotating "super vortices" that trail back behind the system. These powerful structures can extend many rotor diameters back into the flow before they themselves succumb to their own natural vortex instability.

An additional, very transient wake state is sometimes observed at forward speeds near to where the transition from the recirculatory mode to the ground vortex mode might be expected to take place. In this 'intermittent' mode, the rotor produces a succession of short-lived structures that resemble ground vortices, but instead of these vortices becoming a lasting feature of the flow, each subsequent structure is swept up and over the rotor - only to be ingested through the propulsor and replaced shortly afterwards by another, similar structure on the ground just upstream of the system.

The changes in the loading on the rotor (or, alternatively, the changes in control input required to maintain constant loading) are generally quite non-linear and abrupt as the wake of the propulsor transitions through the sequence of states shown in Figure 31, but the intermittent mode is characterised by particularly unsteady behaviour of the system in this respect[5].

When the wakes from two or more rotors interact with the system flying just above the ground, a range of different effects can be observed. The ground vortices from rotors that are mounted in parallel can reinforce each other to form a stronger structure that encompasses a broader swath of the ground outboard of the two rotors than the ground vortex that is created by either of the rotors on its own. The interaction in the space between two rotors in parallel can be highly unsteady, leading to an intense plume of swirling, relatively unstructured vorticity that can rise up between the rotors to form a tall "rooster-tail"-like wake downstream of the aircraft – or, if conditions are just right, precisely at the location of the empennage of the aircraft. The wake of the front rotor of a pair in tandem can force its way underneath the wake of the trailing rotor, causing the trailing rotor prematurely to form its own ground vortex-like structure. Depending on the flight conditions, the arc-like arms of the resultant pair of bow-shaped vortices can either interact and coalesce to form very strong but rather unsteady structures, one on each side of the pair of rotors that created these features, or, instead, remain as distinct features of the flow that propagate along with the rotors as they move through the air.

At the higher forward speeds that are required for the wakes produced by the individual rotors to have lifted clear of the ground, the trailing super-vortices that are created by neighbouring rotors can

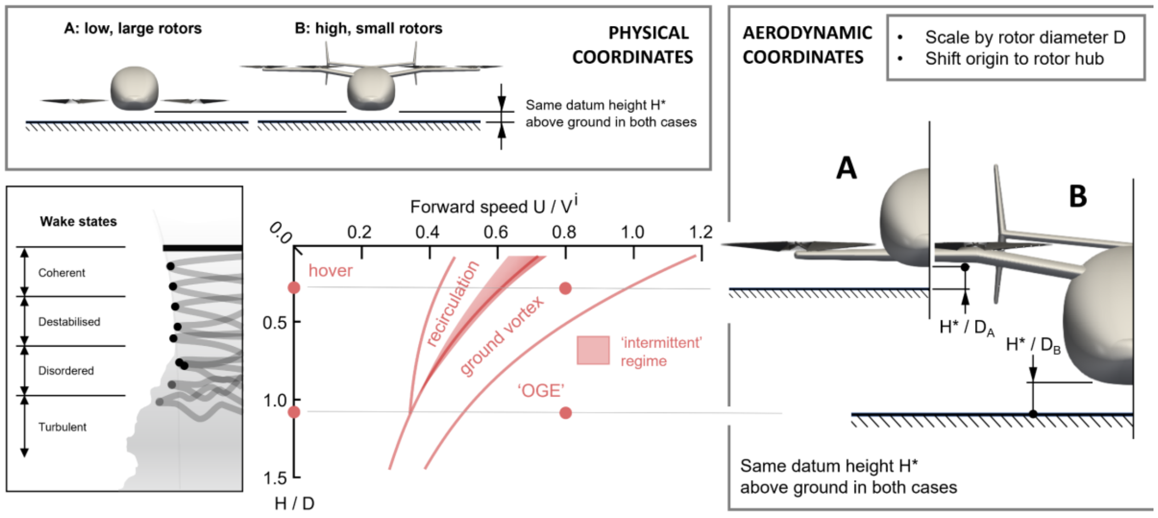


Figure 32: Schematic showing how the Curtiss diagram might be combined with an understanding of how the wake structure evolves below a hovering rotor to predict the differences in aerodynamic behaviour between two aircraft with very different geometric configuration.

interact with each other. In some cases, the interaction causes these vortices to lift up into the flow above the rotor plane, where, for instance, they might stand the chance of interacting with the tail surfaces of their parent aircraft and influencing the flight dynamic characteristics of the system. In other situations, the vortices interact in a much more complex fashion and trail down into the flow behind the system to form a sequence of intricately-interwound vortex spirals. In several cases we have observed, quite radical changes in the structure of the outwash field can accompany relatively minor changes in the speed or height of the system above the ground. Indeed, the examples that follow will show some of the breadth of the aerodynamic behaviour that is possible when multiple rotors are juxtaposed into the various configurations that are representative of current eVTOL practice. We will show too how the fluid dynamics is complicated even further when the fuselage, wings and tail of the aircraft also contribute to the interaction.

11.6 An example of how aircraft design influences the outwash

Detailed phenomenological description of the aerodynamics of these complex aircraft is one thing, but a major aim of the present study was to point the way towards the development of design heuristics that might be used to inform future developments and to support the generation of guidelines that might establish best practice or give early signs of likely problems in a given design.

As an example of how the information presented in this section might usefully be integrated to these purposes, Figure 32 shows how the insights into the structure of the wake of a multi-rotor system that are given by a vortex-based representation of the flow, and in particular the emphasis within this representation on the role of the instabilities that are inherent within such systems in determining the behaviour of the outwash field in specific instances, might be married with Curtiss's representation of the behaviour of the propulsor wake in forward flight to gain an appreciation of how the behaviour of an eVTOL aircraft might depend rather strongly on its configuration.

In this figure, the behaviour of two different aircraft is contrasted – one with relatively large, low-mounted rotors and another with smaller rotors mounted higher up on the airframe. The two configurations are contrasted in the box at the top left of the diagram. The first step to position these aircraft correctly on the Curtiss diagram is to re-scale their geometries by the salient aerodynamic parameter - in this case, the relevant parameter is the diameter D of their respective rotors. This process produces the equivalent, aerodynamically-scaled geometries shown to the right of the plot. We also shift both systems vertically so that the rotors of the two scaled geometries and the representation of the structure of the wake shown at left all share a common datum. If, for the moment, we neglect the role of the interactions between the wakes of the multiple propulsors of the vehicles in obscuring the simplicity of this particular analysis, we can then use Curtiss's state diagram to determine how the structures of the wakes of the two systems might compare at various flight conditions, as defined in terms of the heights of the aircraft above the ground and their forward speeds.

So, for instance, if we compare the properties of the two systems at the same thrust-weighted advance ratio $\mu^* = U_A/V_A^i = U_B/V_B^i$ (or, in other words, at the same flight speeds U_A and U_B if the disc loadings of the two aircraft are the same) and the same *datum* height H^* above the ground, then we can see that, because of the very different *effective* (aerodynamically-scaled) heights of their rotors above the ground, the states in which the wakes of the rotors might find themselves can be very different. For instance, with the vehicles in hover ($\mu^* = 0.0$), the plot would indicate that the rotors of aircraft A might find themselves generating a rather more coherently-structured outwash than aircraft B, and similarly at a forward flight condition with $\mu^* \sim 0.8$ the wakes of the propulsors of configuration B will already have lifted clear of the ground, whereas the rotors of configuration A might still be producing a strong ground vortex. Furthermore, we might postulate on the basis of this diagram that, in accelerating from hover to forward flight, the aircraft with low-mounted, large rotors might have to traverse a range of flight speeds during which the rotors might suffer from significant re-ingestion of their wake, possibly even to the extent of their outwash entering the highly-unsteady 'intermittent' regime, described earlier, over a range of flight speeds. In contrast, the vehicle with smaller, high-mounted rotors might experience a relatively smooth transition into forward flight by avoiding entirely the situation where the outwash enters either of these recirculatory regimes.

Even given the simplicity of the discussion up to this point, and its neglect of many of the features of the outwash field that are relevant to the aerodynamics of multi-rotor vehicles, the value of predictive insights such as those just presented should hopefully be clear. Indeed, we hope that by setting out a clear exposition of the relevant physics, and in introducing a small armamentarium of terminology and insights that can be used to frame the analysis, that the discussion presented in this section of the report will be useful to the reader in providing a relatively simple conceptual basis from which to describe the characteristics of actual eVTOL aircraft configurations – particularly in situations where a reductionist approach is perhaps the only way to come to terms with their aerodynamic complexity.

In the next sections of this report, and in that vein, we consider the aerodynamic properties of the range of different eVTOL configurations that were defined earlier in Section 10. Our particular focus will be to establish the link between the configuration of these aircraft and the characteristics of the outwash that they might produce when operating close to the ground.

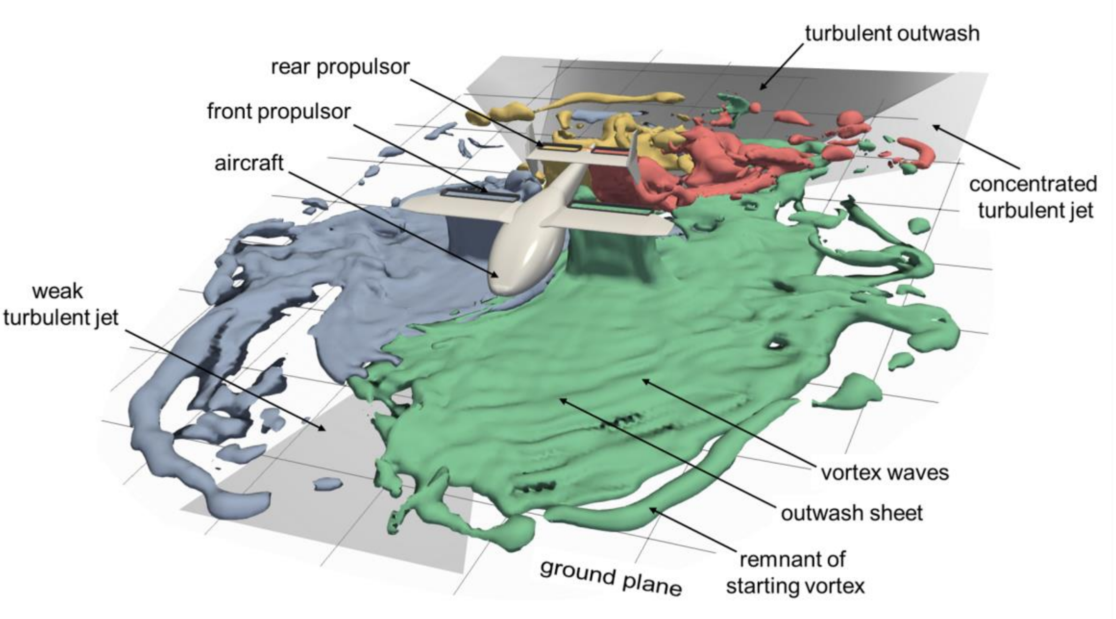


Figure 33: Schematic illustrating some of the typical features of the outwash that is created by a VTOL aircraft when hovering at low altitude above the ground.

12 The Outwash Field produced by eVTOL Aircraft

Before examining in detail the characteristics of the outwash fields that our simulations suggest will be produced by the various eVTOL configurations that were examined as part of this study, it is important first to understand some of the particular characteristics of the numerical approach that was used to generate the data that is presented below. This is particularly necessary if the correct inferences are to be made regarding the likely real-world characteristics of the eVTOL outwash field, as distinct from the numerical simulations thereof that are presented here.

12.1 Numerical Procedure

The process that was used to simulate the aerodynamic behaviour of the various eVTOL configurations was described in some detail earlier (see Section 9). In essence, a numerical simulation is set up in which the geometry of the aircraft being modelled, together with a sufficient volume of air surrounding the vehicle (and, indeed, the ground plane itself) is encapsulated within a grid-like matrix of discrete, small, computational cells.

In order to represent the properties of the flow that the aircraft will generate when flying at the particular operating condition of interest, the equations that govern the evolution of the airflow around the aircraft are approximated within this cellular structure using an appropriate numerical method. In the approach used within this study, the Vorticity Transport Model, described in more detail in Section 9.5.1, is used to yield the history of the flow, expressed in terms of the spatial and temporal variations of the vorticity and velocity in the air surrounding the aircraft, as the system evolves from some appropriately-defined initial state.

In this form of numerical simulation there is always some latitude as to how the initial state for the system is prescribed. The approach that has been adopted here is to assume an ‘impulsive start’ to the system. In this approach, the aircraft is introduced into the flow with the forward speed, height above the ground, bank, roll and pitch attitudes, *etc*., that is appropriate to the flight condition that is being modelled, and, if the aircraft has rotor-like propulsors, with its propellers already rotating. In this initial state, however, the aircraft is yet to produce any of the vorticity that is eventually responsible for the formation of the outwash in the flow below the aircraft.

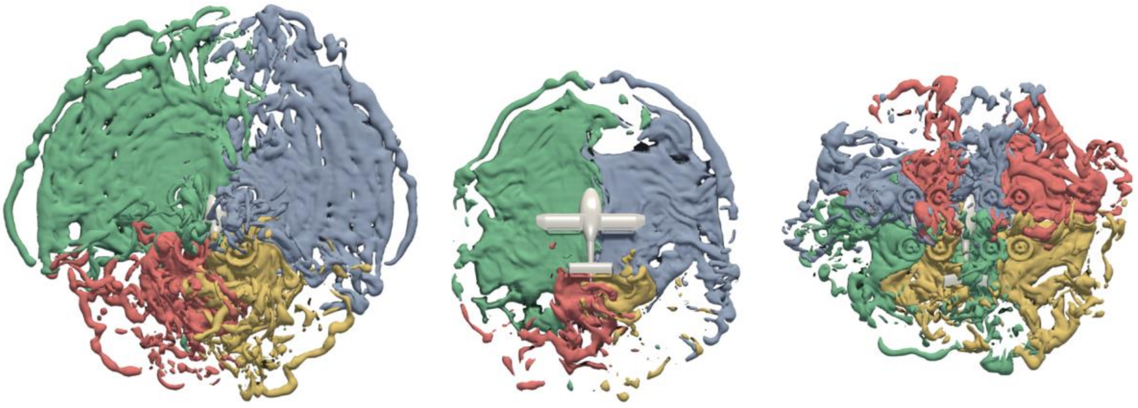


Figure 34: Comparison of the morphology of the outwash fields that are produced by eVTOL aircraft with different configuration when hovering at the same low altitude above the ground. Left: “quad-copter” configuration. Centre: “lift-jet” configuration”. Right: “lift-cruise” configuration.

As time progresses, the flow develops by evolving through a series of transient states in which the structures that arise as a consequence of the particular choice of starting condition either break up and dissipate, or propagate far enough away from the aircraft for their effect on its aerodynamics to be discounted. As these initial structures disperse and dissipate, the longer-term, more persistent features of the flow are created and are left behind in their place.

The intent behind this procedure is that, as the calculation advances, the simulated flow should approach ever more closely the state that the real flow would adopt in the long term, even if the starting conditions that were imposed on the real flow were significantly different in character to those used to initiate the numerical simulation.

The simulation thus has to be run for sufficient time for the principal features of the matured flow to establish themselves as the outwash spreads out across the ground plane.

Given the evolutionary character of the simulation and the fact that calculation times are inevitably limited by available resources, it should always be borne in mind - and especially when interpreting the snapshots of the flow structure that are shown in the figures below - that the most peripheral features within the simulated outwash field could quite feasibly still contain artifacts of the specific initial conditions that were imposed on the system.

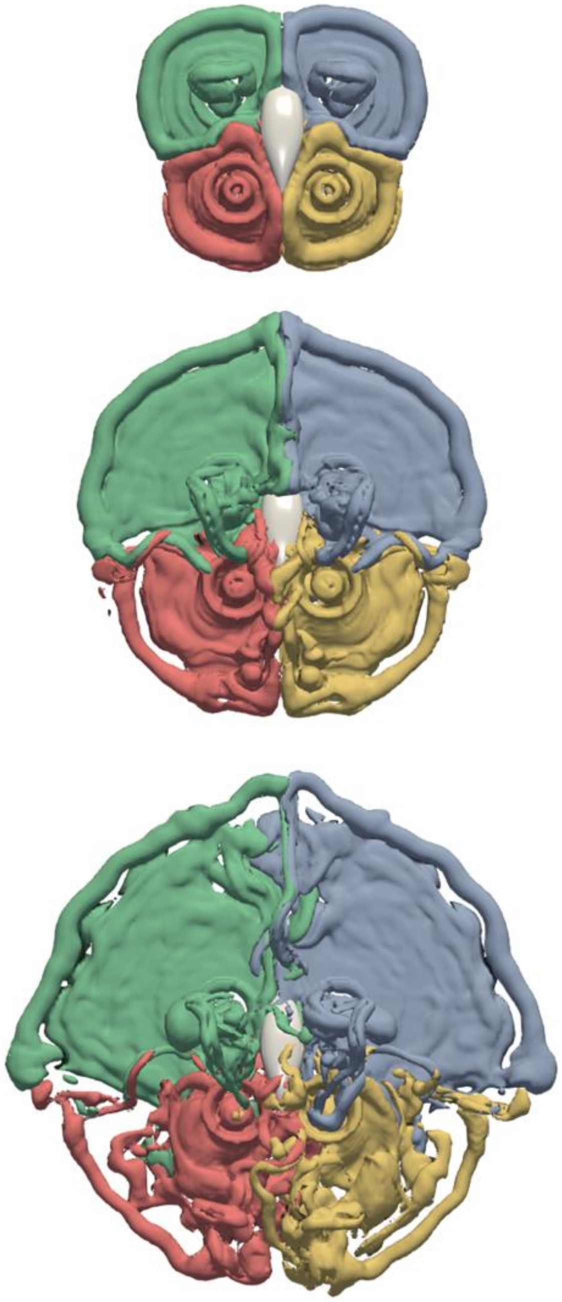


Figure 35: Early stages in the evolution of the flow that is created by the "quad-copter" eVTOL configuration, showing the confluence of the wakes that are produced by the individual rotors and the subsequent symmetry-breaking within the flow that leads to the observed long-term structure of this vehicle's outwash field. Time increases from top to bottom.

In other words, certain features within the renditions of the flow that are produced by the numerical simulations need not necessarily be representative of the longer-term structure of the established outwash field, or indeed of the outwash field that is produced by the equivalent real-world system. As long as this technicality is borne in mind, and the data is properly interpreted in its light, the utility of the modelling approach that has been adopted here in allowing specific structures within the flow to be traced back to their origins generally outweighs the potential advantages of adopting a methodology that proceeds directly to producing a notional "long-term" or "steady-state" solution to the fluid dynamic problem - as some numerical techniques claim to do. Indeed, how spurious the concept of a steady state might be, especially in the presence of the highly-interactive vortical flows that characterise the outwash problem, should already be apparent from the analysis that was presented earlier in Section 11.

Indeed, once the flow has evolved for a sufficiently long period of time, the action of the inherent instabilities within the vorticity field can be so effective in disordering the structure of the outwash field that it can be very difficult indeed to determine the origin of specific flow features or to infer the details of the underlying physics from a simple snapshot of the flow at any specific instant in time. Unfortunately this is where the static nature of the printed medium becomes a distinct disadvantage – a tremendous amount of information and insight can be gleaned by watching an animation of the flow as it develops.

We will do our best to make up for this deficiency in the presentation of our analysis by exploiting one of the principal advantages of representing the flow in the way that we have done, and will present sequences of snapshots of the flow at various stages during its evolution, especially where this helps to expose the origin of the various relevant physical structures within the outwash field below the aircraft that is being modelled.

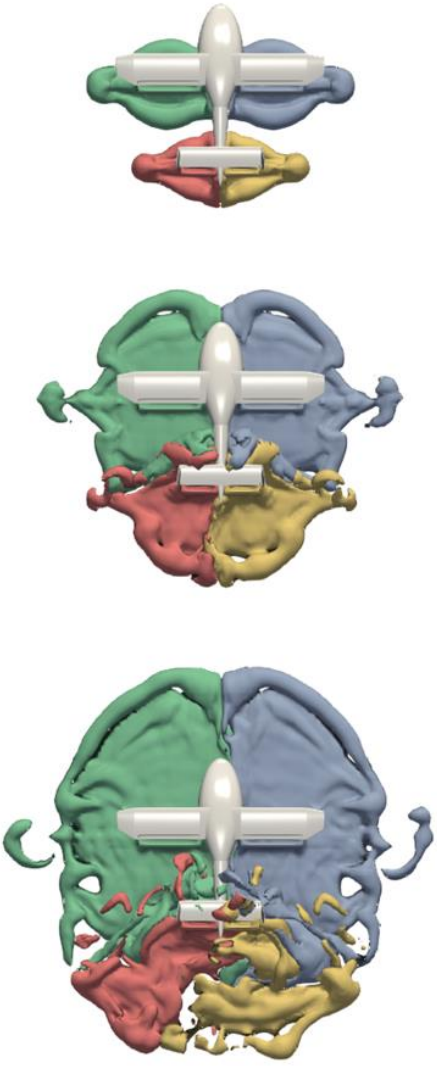


Figure 36: Early stages in the evolution of the flow that is created by the "lift-jet" eVTOL configuration, showing the confluence of the wakes that are produced by the individual rotors and the subsequent symmetry-breaking within the flow that leads to the observed long-term structure of this vehicle's outwash field. Time increases from top to bottom.

In the interests of generality, and to allow the scaling analysis presented in Section 8.2 to be exploited a little later in this element of the work, the benchmark "helicopter" configuration, defined in Section 10.6, that has eVTOL-like disc loading will be used throughout the analysis to provide the reference configuration against which the properties of the other systems can be compared. The radius of the rotor of this aircraft is denoted by R^* and the downwash velocity that it produces by V^*. Since all the configurations that were tested were set up to have the same disc loading, V^* takes on special significance as the *reference* induced velocity for the entire set of aircraft.

12.2 The Structure of the Outwash Field

The key characteristics of the outwash field that is generated by an aircraft that uses multiple propulsors to support its weight when hovering above the ground are illustrated in Figure 33. Although this figure shows a numerical rendition, obtained using the Vorticity Transport Model, of the outwash field that is created by our particular representative of the "lift-jet" configuration when hovering in still air at a height of 0.50 R^* above the ground, the figure shows many of the typical features of the outwash field that are created more generally by the entire set of vehicles that was simulated as part of this study.

The structure of the outwash field is visualised by plotting an iso-surface in the flow on which the vorticity has constant magnitude, and where the parameters of the iso-surface have been set to reveal the overall morphology of the field rather than the details of its internal structure. The vorticity produced by each of the individual propulsors has been rendered in a distinct colour to aid analysis of the structure of the flow.

The outwash field can typically be divided into several sectors, one associated with each of the aircraft's individual propulsors. The character of the flow within each sector is broadly determined by the ratio of the height of the associated propulsor above the ground to its own radius, as per Figure 26. If this ratio is small, the outwash within the sector generally consists of a thin, relatively smooth sheet of vorticity above the ground, and thus the associated velocities within the outwash in these sectors are also relatively steady. If the ratio is large, the flow downward from the propulsor has had the time to succumb to its inherent vortical instability before it reaches the ground, and the outwash in the associated sector will be chaotic and unsteady. With the ratio of propulsor height to radius within a narrow band of intermediate values, the inherent vortical instabilities cause the flow in the outwash to coalesce into a series of clumped vortex waves, which can then spread out above the ground. These waves induce a velocity field that would be experienced by an observer located in the outwash as particularly unsteady but also as having a characteristic buffet frequency.

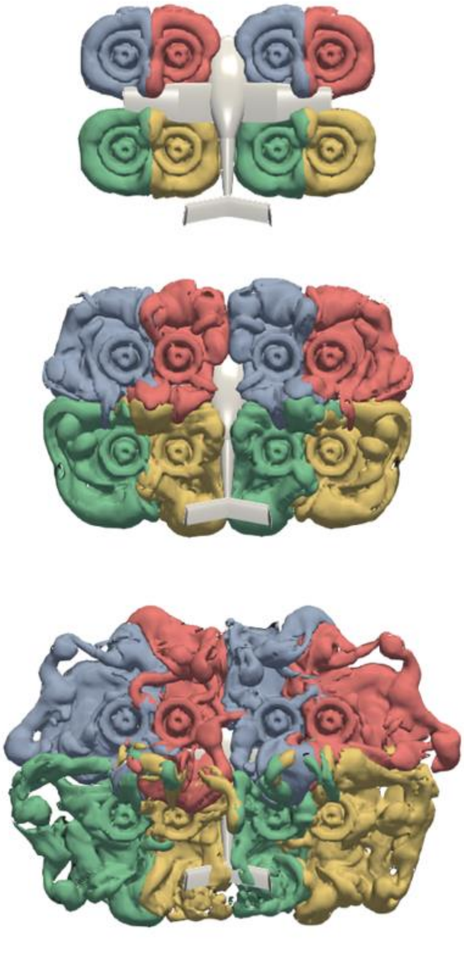


Figure 37: Early stages in the evolution of the flow that is created by the "lift-cruise" eVTOL configuration, showing the confluence of the wakes that are produced by the individual rotors and the subsequent symmetry-breaking within the flow that leads to the observed long-term structure of this vehicle's outwash field. Time increases from top to bottom.

The structure of the outwash field becomes particularly complex at the confluences between the flows that are generated by the individual propulsors. As described in Section 11.4, the flow in these parts of the outwash is characterised by the presence of upwards fountains of vorticity and, particularly at the confluence of the wakes of propulsors that have dissimilar ratios of height above the ground versus radius, by the generation of localised standing vortices in the flow. In many cases these structures are located in parts of the flow where they are able to interact with the airframe of the aircraft in highly unsteady fashion, thus potentially inducing the range of pathologies described in Section 7.2.2. As also described in Section 11.4.2, the confluence of the wakes of two propulsors is invariably associated with the production of a highly turbulent jet of flow outwards along the ground within a narrow sector of the outwash field. In Figure 33, the tell-tale signs are visible in the vorticity field of the existence of two very powerful such jets on either side of the vehicle that are directed outward along the confluence of the flows that are generated by the front and rear propulsors. A similar, but weaker structure is visible outward along the confluence of the flows from the forward two propulsors of the system.

Also clearly apparent in the figure are the remnants of the 'starting vortex' that was created by the propulsors in response to the way in which the simulation was initiated. Although this feature is undoubtedly an artifact of the numerical process that was used to simulate the flow around the vehicle, it will be shown very shortly how the outflow field within the numerical simulations generally comes into being in a much more orderly and structured form than renditions of the flow such as that presented in Figure 33 might suggest. The process whereby the simulated outwash field loses its initial symmetry and the long-term structure of the flow eventually emerges can be understood very readily in terms of the dynamics of the starting vortex.

This connection between the early history of the flow and its observed final state allows the various features that are observed in the outwash fields of any of the aircraft simulated here to be characterised and identified - even, as is often the case, when the flows have become so chaotic and disordered in the long term that their underlying structure has been obscured appreciably by the sustained action of the vortical instabilities that are always inherent within the flow.

Figure 34 contrasts the long-term structure of the outwash fields that are produced by the representatives of the "quad-copter", "lift-jet" and "lift-cruise" eVTOL configurations that were simulated during the course of this study. The perspective within each rendition is from above the vehicle, showing clearly the partition of the outwash into a set of sectors, each associated with one of the individual propulsors of the vehicle. The aircraft are all hovering so that their horizontal datum is at 0.25 R^* above the ground plane, in other words at a height where in practice the wheels of the real aircraft might be just clear of the ground.

In this condition, the "quad-copter" finds its forward rotors extremely close to the ground, and consequently the outwash field in the associated sectors of the flow is relatively smooth and sheet-like. Some evidence is visible further out into the flow of the coalescence of the vorticity within these sheets to form the sequence of waves that is characteristic of a flow in which the vortical instabilities have had more time to disrupt the orderly progression of the individual rotor tip vortices out across the ground plane. The periphery of the sheet is marked by the presence of the remains of the starting vortex. Were the simulation to have proceeded for any longer, this vortex would have been expected to propagate further outwards into the flow and eventually to have disintegrated entirely, its structure having being replaced by the remnants of the vortex waves that can be seen to be propagating out behind it.

The rear rotors of this particular configuration are higher above the ground than the front rotors. This geometric asymmetry causes the interaction between the wakes produced by the front and rear rotors to be remarkably complex in this case. The flow from the front rotors undercuts that from the rear rotors to produce a double-layered, highly turbulent flow in the outwash behind the vehicle similar to that shown in the schematic at bottom right in Figure 28. Also clearly visible in the figure is that some of the vorticity from the front rotors ends up being ingested into the rear rotors – in a process that results in appreciable unsteadiness in the thrust and pitching moments that are produced by the system. The signature in the vorticity field of the presence of a strong but relatively broad outwards jet is visible in the confluence of the flows that are produced by the two forward rotors, and the presence of two more powerful and concentrated features can also be discerned along the confluence of the flows that are produced by the forward and rear rotors on either side of the vehicle.

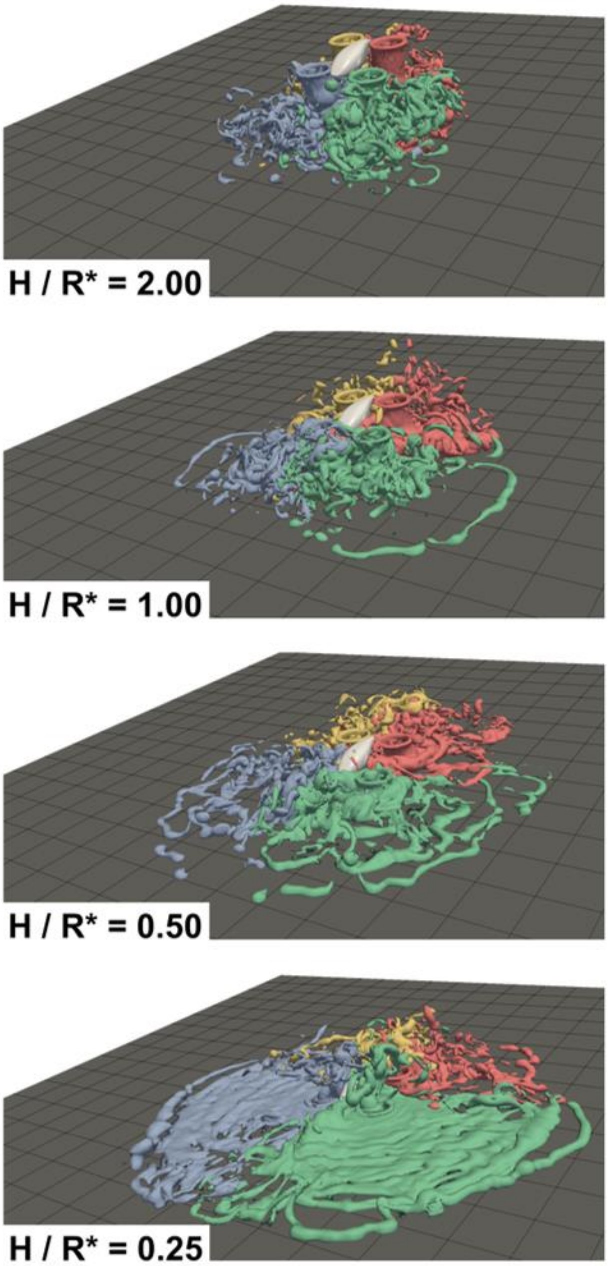


Figure 38: Structure of the flow produced in the outwash field below the "quad-copter" eVTOL configuration with the aircraft hovering at various heights H above the ground.

The central image in Figure 34 shows the outwash field that is produced by the representative of the "lift-jet" configuration of vehicle that was simulated. The structures produced in its outwash field are superficially similar to those produced by the quad-copter, as might perhaps be expected given the similar layout of the propulsors of the two aircraft. Some subtle differences are apparent, however. Even though the propulsors of the lift-jet aircraft are located higher above the ground (relative to their effective radius) than those of the quad-copter, the absence of discrete tip vortices in the wake of its jet-like thrusters causes the flow to succumb more slowly to its inherent vortical instability. Thus the flow out along the ground plane to the front of the vehicle is able to remain sheet-like for quite some distance before developing the wrinkles that are characteristic of the formation of vortex waves. When these waves do begin to develop, the associated vorticity tends to concentrate to form structures that are aligned transverse to the longitudinal axis of the aircraft, rather than forming roughly concentric, outwards-propagating rings as in the case of the quad-copter. This difference in behaviour undoubtedly arises in the peculiarities of the flow that is produced by propulsors with slot-like rather than disc-like geometry, and the associated element of directionality to the buffeting that will be induced on any object that finds itself immersed within the outwash field of this particular type of aircraft adds an extra element of complication to assessing the influence of its outwash field on the vehicle's surroundings.

Possibly as a consequence of the closer alignment of the flows on either side of the confluence of the flows that are produced by the front propulsors of the system, the jet that is formed out to the front of the aircraft is considerably weaker than in the case of the quadcopter. The jets that would be expected to form on either side of the aircraft along the confluence of the out-flows from the front and rear propulsors are much more obvious by comparison, but their trajectory also appears to be strongly influenced by their interaction with an extremely unsteady zone of outwards flow that develops behind the aircraft. What appears to be happening in this sector of the outwash field is that the flow from the two rear propulsors is prematurely being turned parallel to the ground by its interaction with the flow backwards from the forward two propulsors. By the time the wakes of the rear propulsors begin their outwards propagation along the ground plane, they are thus still in the very early stages of being disordered by the action of their inherent vortical instabilities. The outwash field is thus dominated by the presence of the large, semi-coherent but highly dynamic structures that are characteristic of the early stages of the decay of the wake (see Section 11.2) rather than by the presence of the structures that would be associated with the wake in a much more advanced state of decay - as is seen for instance in the outflow to the rear of the quadcopter.

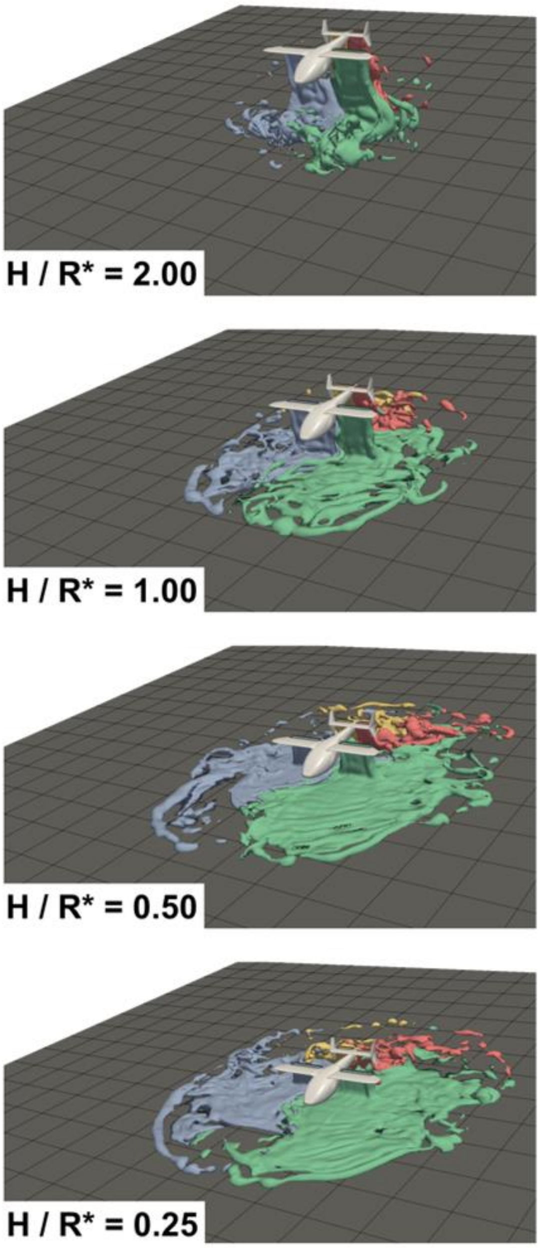


Figure 39: Structure of the flow produced in the outwash field below the "lift-jet" eVTOL configuration with the aircraft hovering at various heights H above the ground.

A highly significant feature of the outwash field of the lift-jet is the stationary vortex that is formed transverse to the longitudinal axis of the aircraft, just under the fuselage at the confluence between the flows from the forward and rear propulsors. The interaction of this vortex with the empennage of the aircraft would be a potential source of concern given its possible influence on the aerodynamic loads on this part of the aircraft - and hence on the trim of the vehicle during operations close to the ground.

Finally, the right-hand image in Figure 34 shows the outwash that is produced by the most symmetric representative of the "lift-cruise" configuration that was analysed as part of this study. Recalling that the overall disc area of all the simulated aircraft was held constant from configuration to configuration as the most natural way of ensuring that the comparison would be conducted on the basis of equal disc loading, this aircraft, with its eight rotors, has propulsors with significantly smaller individual area than those of the quadcopter or lift-jet aircraft that were simulated here. Given also the relatively high mounting of the rotors on the aircraft, the ratio of the height of the propulsors above the ground to their radius is great enough for their wakes already to be in an appreciably turbulent state by the time that they interact with the ground - even with the aircraft operating at the very low altitude represented in the figure. The outwash that develops is thus largely turbulent in character, and spreads out around the aircraft to envelop it in a largely amorphous and unstructured cloud of vorticity. Indeed, any structure within the outwash field is very difficult to discern within the plot as shown.

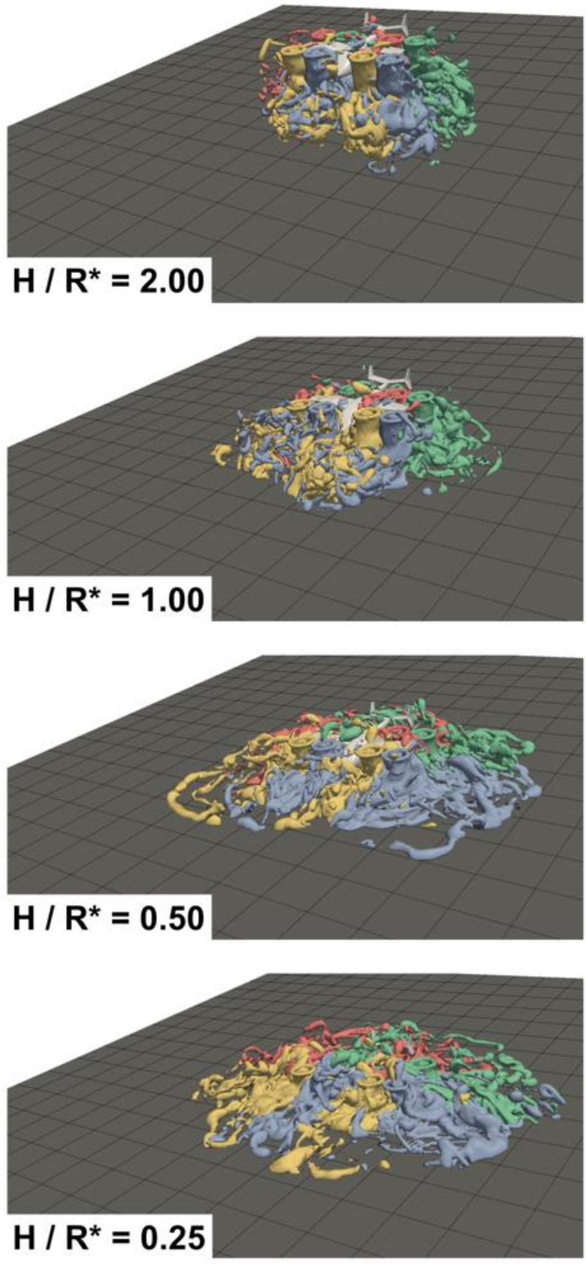


Figure 40: Structure of the flow produced in the outwash field below the "lift-cruise" eVTOL configuration with the aircraft hovering at various heights H above the ground.

Figure 35, Figure 36 and Figure 37, however, each show a series of snapshots of the outwash field that is produced by each of the simulated aircraft configurations at much earlier stages in the evolution of the flow. The top image in each case shows the flow very soon after its inception. The doughnut-shaped structure associated with each propulsor is its starting vortex, and the situation is shown where the starting vortices have propagated down into the flow below the aircraft and have just made contact with the ground surface. The clear connection between the symmetries of the flow at this early stage in its evolution and the layout of the propulsors is obvious. Again, the inherent instability of the vortices plays a crucial role in the subsequent evolution of the flow.

Indeed, the symmetrical state of the outwash field shown in these images does not persist for long. The middle set of images shows the symmetry of the system just beginning to break as segments of the starting vortices begin to interact with each other and deform. The lower set of images shows the structure of the flow a short time later - once the dynamics of the flow has caused quite considerable distortions of the geometry of the vorticity field away from its initially symmetrical state. The keeneyed observer will note the early stages of formation of the hairpin-like structures that eventually coalesce to create the vortical foundation of the jets that invariably tend to form along the confluence of the wakes of the individual propulsors in the fully-developed flow. On contrasting the vorticity distributions shown in the middle and lower plots, the origin of the turbulent sectors of the outflow in the growth of perturbations to the originally-smooth sheet of vorticity inboard of the starting vortex should also be clearly apparent in all cases.

Figure 37 for the "lift-cruise" configuration is particularly instructive, yielding, as it does, additional insight into the inherent structure within the flow that is produced by this configuration of vehicle and complementing the plot of the later stages of the evolution of the flow shown in Figure 34. The interaction between the starting vortices can clearly be seen to initiate the envelopment of the wing and fuselage of the aircraft within the vortical cloud, and the characteristic signatures of the early-stage development of outwards-directed jet-flows can be seen at multiple locations around the periphery of the aircraft.

12.2.1 Influence of Height above Ground

The analysis so far has only considered the characteristics of the outwash field produced by the various aircraft when hovering at a particularly low height above the ground. As might be expected from the analysis presented in Section 11.3, the character of the outwash field is in fact strongly dependent on the height at which the aircraft finds itself hovering above the ground. Figure 38, Figure 39 and Figure 40 illustrate the relationship between the structure of the outwash field and the height of the aircraft above the ground for each of the eVTOL configurations that were simulated as part of this study.

The information that is presented in these figures is most readily interpreted by making use of the analysis that was presented earlier in Section 11.3. With the vehicles at the greatest height above the ground that is represented in the figures (*i.e.* H/R^* = 1.0), the flows downward from the individual propulsors have in all cases sufficient space to succumb to their inherent vortical instability before they reach the ground. The outwash field is thus characterised by a relatively small vortical footprint on the ground and generally by a flow that is principally turbulent in character.

As the height of the system above the ground is reduced, a point arises (depending on the size and configuration of the propulsors) where the flow reaching the ground still has appreciable structure, and this generally results in a change in character of the outwash field that is produced by the aircraft that is consistent with the information plotted in Figure 26 and Figure 28. Given the relatively stable wakes of its individual propulsors, the simulated representative of the "lift-jet" configuration shows this transition most clearly when the height of the vehicle above the ground is reduced to around 1.0 R^*, whereas the outwash of the quad-copter changes character with the vehicle somewhat lower above the ground. The simulated representative of the "lift-cruise" configuration, as might be expected from the analysis presented above, continues to produce a turbulent outwash all the way until its wheels touch the ground. As the height of the quadcopter above the ground is reduced from about 0.50 R^* to about 0.25 R^*, an interesting secondary transition in the structure of the outwash is observed as the ground sheet changes from being characterised by the presence of multiple vortex waves to having a much smoother structure.

12.3 The Velocity in the Outwash Field

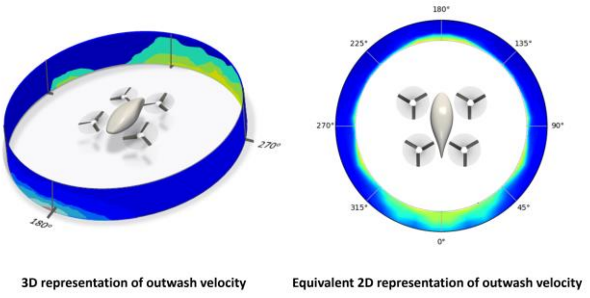
The fundamental question then arises as to how the velocities in the outwash field are influenced by the configuration of the aircraft, particularly in the light of the various visualisations of the flow presented above that reveal the very strong influence of the geometry of the aircraft and its operating condition on the structure and dynamics of the flow. Although analysis of the radial, swirl and vertical components of the outwash field all have their utility in trying to understand the relationship between the velocities in the outwash and the structure of the flow that is created below the aircraft, the most direct and straightforward appreciation of the effect of aircraft configuration in influencing the properties of the outwash field, particularly with the vehicle in hover, is obtained by examining solely the component of the velocity in the outwash field that is directed radially outwards from the vehicle.

Figure 41 shows, in schematic fashion, how the radial component of the velocity in the outwash field will be represented throughout the analysis that follows. The physical situation is represented in the schematic at left. A cylindrical boundary, surrounding the vehicle of interest, is immersed in the outwash field, and the radial component of the velocity is sampled at a set of points located on this 'measurement surface'. The variation of velocity from place to place on the measurement surface is then represented by the superimposed contour plot. An equivalent but more manageable representation of the distribution of radial velocity on the measurement surface is then obtained, as shown in the schematic at right, simply by 'flattening' the diagram into two dimensions by mapping the velocity distribution on the cylindrical measurement surface onto the annular-shaped region as shown.

In the figures that follow, the cylindrical measurement surface will consistently be given a radius of 2.5 R^*, and will be centred between the rotors of the particular aircraft that is being considered. This particular radius was selected to represent broadly the characteristics of the 'minimum enclosing circle' (or 'D-value') that is gaining acceptance in the vertiport design community[54,55] as a measure of the range out to which a particular aircraft might have 'significant impact' - however this term is most appropriately defined - on its surroundings. Rather than varying the radius of the measurement surface in proportion to the vehicle's dimensions, however, the same radius is maintained throughout the present analysis in order to allow the effects of aircraft configuration on the strength and character of the outwash velocity field to be more directly exposed.

As might be suspected from the analysis of the structure of the outwash that is produced by the various vehicles at different heights above the ground that was presented in Section 11.3, the velocities in the outwash field are strongly influenced by the height at which the system is set to hover above the ground. Space precludes a full analysis of this effect, however, and data is presented here only for the case where the vehicle of interest is set to hover with its datum at a height of 0.25 R^* above the ground plane. For the configurations modelled in this study, this corresponds essentially to the situation where the wheels of the real aircraft would just have lifted clear of the surface. Indeed, even this limited set of data provides a very clear insight into the likely characteristics of the outwash field that might be produced by the various types of eVTOL aircraft that were analysed as part of this study.

The velocity field that is created by a hovering helicopter or eVTOL aircraft is highly unsteady, even with the aircraft in equilibrium flight, and thus in the interests of economy we seek to represent the flow via a *small* set of parameters that are able to encapsulate the salient features of the outwash field despite its inherent fluctuations and variations over time. In this vein, we follow established practice[1,2] and present three different parameters in order to represent the principal characteristics of the velocity within the outwash field. The first parameter is simply the mean velocity, defined as the long-term time-average of the velocity as measured at the point of interest. Secondly, the RMS component of the velocity, defined as the square root of the time-average of the squared deviation of the velocity from the mean, is used to provide a measure of the unsteadiness of the flow at the particular point of interest. Thirdly, the maximum velocity recorded at the point of interest is also presented in order to allow an appreciation of the most extreme excursions in the properties of the flow that might be encountered within the outwash field.



3D representation of outwash velocity

Equivalent 2D representation of outwash velocity

Figure 41: Schematic showing the representation of the outwash velocity field on a cylindrical "measurement surface" that surrounds the aircraft of interest.

This fundamentally statistical representation of the flow has its limitations, however, and the caveats regarding the validity of this representation that were presented in Section 5.1, and the various misconceptions regarding the character of the outwash field that it might engender, should be borne firmly in mind. Simply put, the existence of a mean component to the velocity implies a coherence to the flow that is not necessarily present, the RMS velocity lends undue weight to the most extreme, and possibly thus also the least representative, deviations of the velocity from the mean, and the maximum velocity is not a robust measure in the sense that any value that is obtained for this parameter could in principle be exceeded were the system to be observed for long enough.

Notwithstanding these reservations, Figure 42 shows the distribution of outwash velocity surrounding the two benchmark helicopter-like configurations defined in Section 10.6, represented in terms of the distribution of the mean, RMS and maximum radial velocities as measured on the cylindrical measurement surface defined earlier. In both cases, the measurement surface is centred on the axis of rotation of the aircraft's rotor. It is important to realise too that the velocities in both cases have been scaled by the induced velocity V^* that is produced by the helicopter with eVTOL-like disc loading. This scaling allows the analysis derived in Section 8 to be brought to bear later in comparing the characteristics of the outwash fields that are produced by different aircraft configurations.

It is clearly apparent from the plots that the distributions of outwash that the vehicles produce deviate quite considerably from having the axisymmetry that the simpler theories would predict for vehicles having only a single rotor. The fact that the rotor has an inherent handedness as a result of the particular selection of its direction of rotation, together with the presence of the fuselage, destroys the geometric axisymmetry of the system, and, indeed, visualisations of the flows that are produced by these vehicles show very clearly how the aerodynamic interaction between the fuselage and the tip and root vortices that are produced by the individual blades of the rotor is responsible for skewing the wake preferentially towards the starboard quarter of the vehicle.

The mean velocities in the outwash field at a distance of 2.5 R^* from the reference system are estimated by the numerical analysis to be at most about 0.67 V^*, reducing to about 0.57 V^* for the helicopter with more conventional disc loading. These values are consistent with expectations, and, indeed, the differences between the mean and maximum velocities produced in the outwash beneath the two systems can be explained almost entirely in terms of the difference in disc loading between the two aircraft (see Section 8.2). Indeed, the influence of the difference in size of the aircraft relative to the radius of the cylinder on which the outwash was measured appears to be rather small in the case of the mean and maximum velocities produced by these particular aircraft geometries. This suggests that the sensitivity of the geometric amplification factor $k^c(r,\psi)$ to aircraft configuration is particularly weak in this specific instance. Such is not entirely the case for the unsteadiness in the velocity field, however - the helicopter with the more highly loaded rotor producing a disproportionately higher RMS velocity than simple scaling by the induced velocity might suggest.

The distributions of outwash velocity, on the same measurement surface, are compared in Figure 43 for the various eVTOL configurations that were examined as part of this study. To aid in comparing the

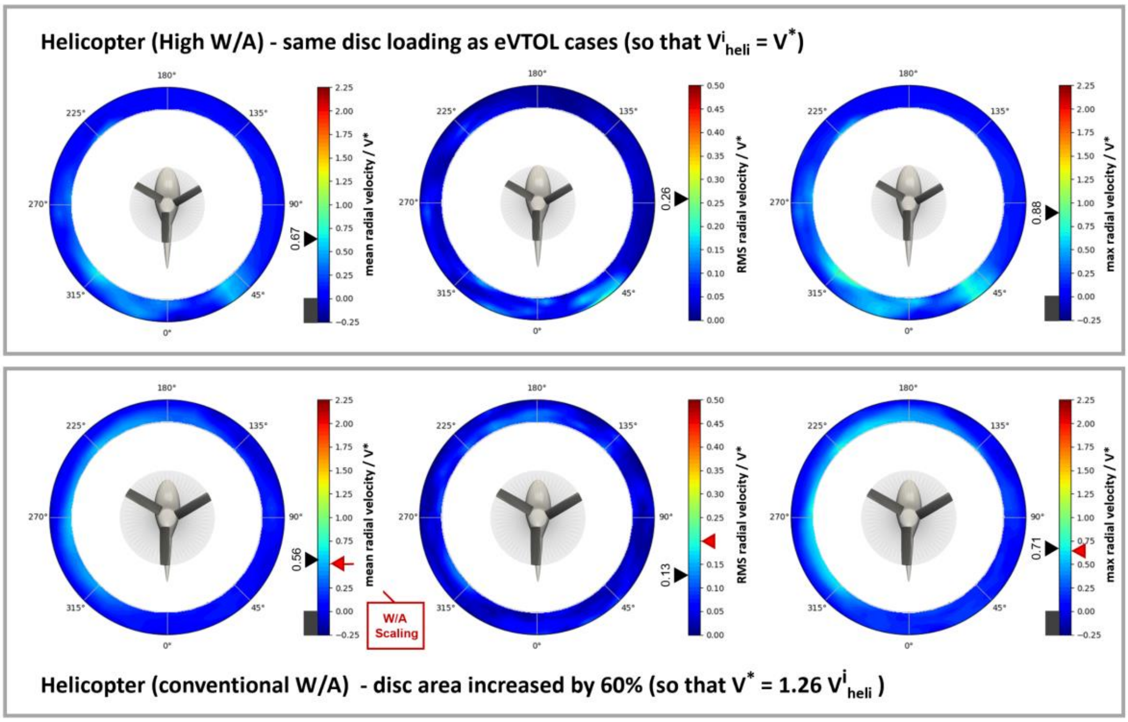


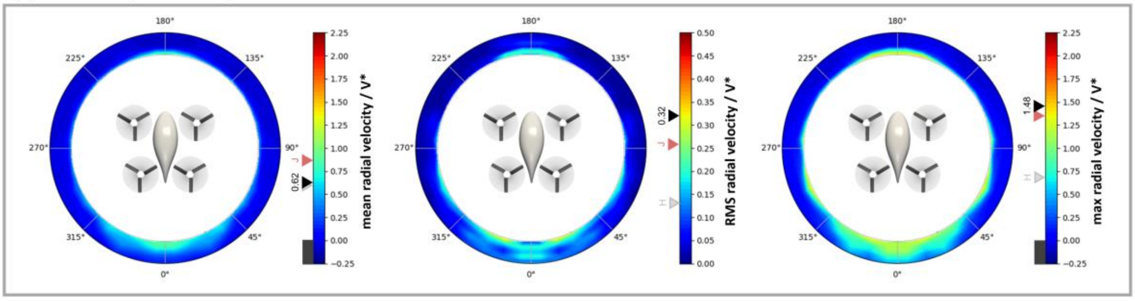
Figure 42: Radial component of outwash velocity below the two reference helicopter configurations when in hover at low altitude above the ground, as measured on a cylindrical surface located at a distance of 2.5 R from the rotor axis.*

properties of the different systems, the maximum observed values of the mean, RMS and maximum radial velocities in each case are indicated in each figure by the small, triangular markers attached to the velocity scales. These values are used later in this section to characterise the strengths of the outwash fields that might be produced by the various systems that were examined relative to each other, and indeed to compare the strengths of the outwash fields that are produced by these various eVTOL configurations to the equivalent properties of more conventional helicopters.

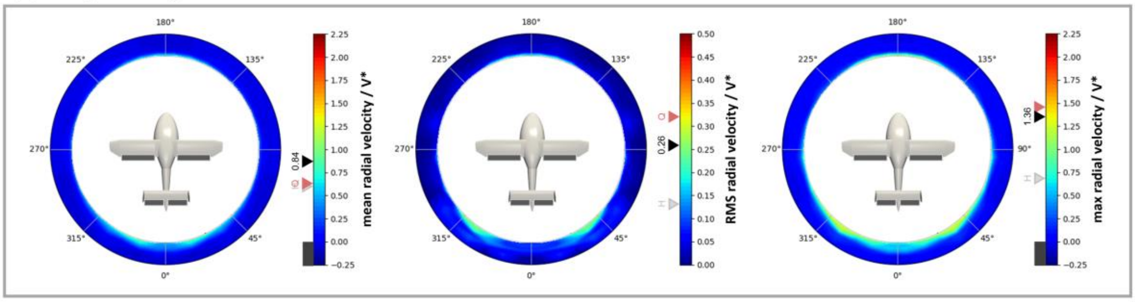
The top set of diagrams in Figure 43 show the distribution of the radial velocity within the outwash field for the "quad-copter" aircraft configuration. The presence of the deep, turbulent outflow behind the vehicle shown in Figure 34 and Figure 38 is clearly evident in the regions of elevated mean and maximum velocity in these plots. Similarly, the presence of the concentrated jets in the flow out along the ground plane can be inferred from the locations of the various peaks in the measured RMS and maximum velocity. Indeed, the effects of the forward-pointing jet in inducing a highly unsteady and powerful outwards flow at an azimuth of 180 degrees with respect to the aircraft is clearly evident in the plots. The characteristic signatures of the jets that are formed along the confluence of the outflows from the forward and rear sets of rotors are also particularly notable in the plots at azimuths of around 70 and 290 degrees.

The middle set of diagrams in Figure 43 show similar information for the "lift-jet" configuration. Perhaps not entirely unsurprisingly, given the broadly similar layout of its propulsors, this system produces a distribution of outwash velocity on the measurement surface that bears some resemblance to that of the “quad-copter” configuration shown in the top diagrams in Figure 43. The jet out to the front of the aircraft, although still present, is significantly weaker, however, and the turbulent flow to the rear of the vehicle is narrower and, by inference from the relative contribution of the mean, RMS and maximum velocity to the signature of this structure in the plots, is characterised more by the

(a) "Quad-copter" configuration



(b) "Lift-jet" configuration



(c) "Lift-cruise" configuration

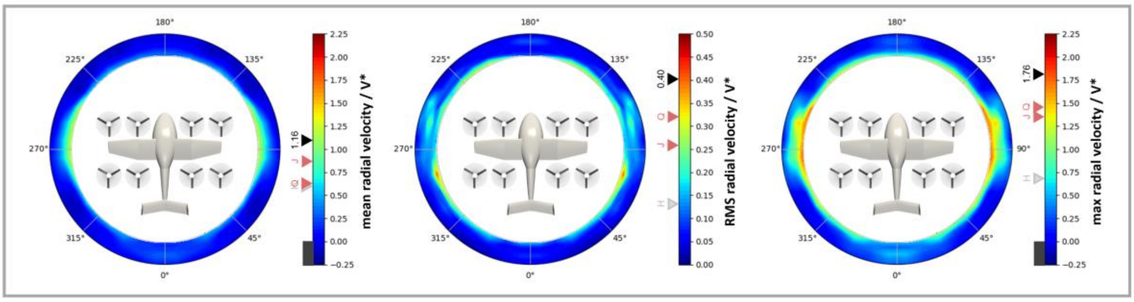
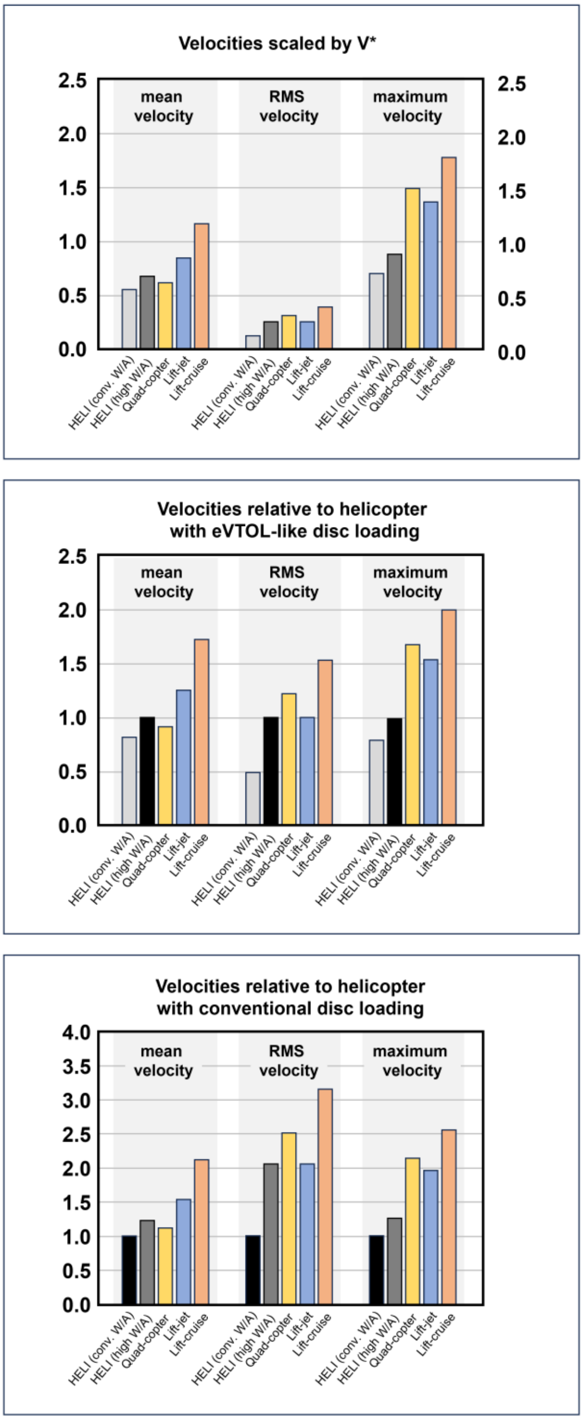


Figure 43: Mean, RMS and maximum values of the radial component of the outwash velocity produced by various eVTOL configurations when in hover at low altitude above the ground, as measured on a cylindrical surface located at a distance of 2.5 R from the centroid of the aircraft's propulsors. Top: "quadcopter" eVTOL configuration. Middle: "lift-jet" eVTOL configuration. Bottom: "lift-cruise" eVTOL configuration.*

intermittent ejection of large-scale vortical structures into the flow than by the presence of an established turbulent wake as in the case of the quad-copter. Again, the presence of turbulent jets along the confluence of the wakes that are produced by the front and rear propulsors is clearly evident from the presence of their characteristic signatures in the plots of RMS and maximum velocity.

Finally, the bottom set of diagrams in Figure 43 show the distribution of the radial velocity within the outwash field for the basic "lift-cruise" configuration with symmetric rotor layout. In this case, the plot of the distribution of the outwash velocity on the measurement cylinder reveals the flow at this distance from the system to be characterised by particularly strong, jet-like features that are directed out along the spanwise axis of the wing. The strength of these features is undoubtedly influenced by the proximity of the most outboard rotors of the vehicle to the measurement surface, illustrating most clearly of any of the examples presented here the effect of aircraft configuration on the likely distribution of outwash below the vehicle. The presence of the jets that would be expected to form along the confluence of the wakes that are produced by the individual rotors of the aircraft can also be inferred from the positions of the local peaks in the distributions of the RMS and maximum velocity on the cylindrical measurement surface.


Velocities scaled by V*

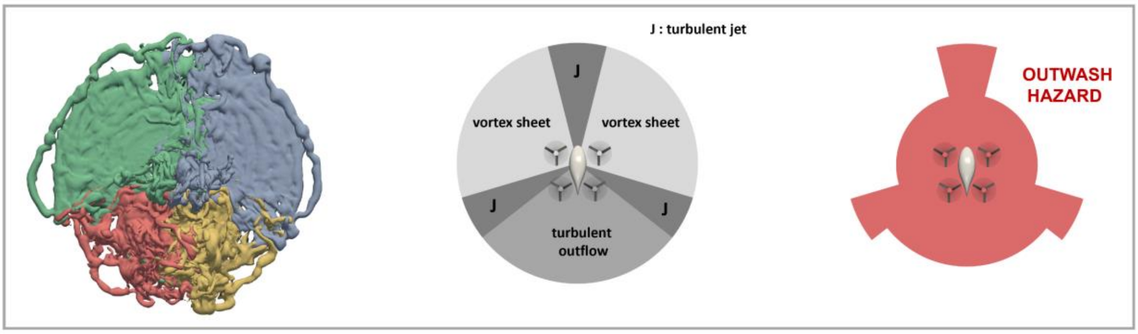
Velocities relative to helicopter with eVTOL-like disc loading

Velocities relative to helicopter with conventional disc loading

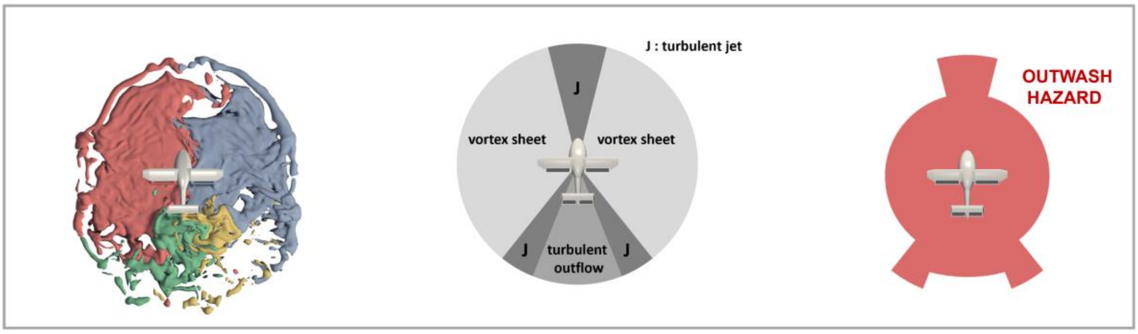
Figure 44: Quantitative comparison of the outwash velocities that are likely to be produced by eVTOL aircraft with various different configurations.

Figure 44 condenses the data from Figure 42 and Figure 43 into a series of plots that allows the characteristics of the outwash fields that are generated by the various configurations to be compared in more quantitative terms. The top plot summarises the data presented in from Figure 42 and Figure 43 by presenting the maximum observed values of the mean, RMS and maximum velocities for each configuration that was tested, scaled in each case by the induced velocity V^* that is produced by the reference helicopter with eVTOL-like disc loading. This plot allows the level of unsteadiness in the outwash to be judged relative to the magnitude of the mean flow for each configuration. The amount by which the velocity in the outwash might potentially exceed the mean on occasion, if the system is observed for sufficient time, can also be inferred from the data for the maximum velocity that is presented in this plot. It is interesting to note that for the helicopters, the maximum velocities observed in the wake are very closely matched by the sum of the mean and the RMS components of the velocity, suggesting that the fluctuations in the outwash that is produced by the helicopter are largely periodic in nature. Indeed, this observation is supported by the limited experimental data that is available. On the other hand, the information presented in this figure also shows that the outwash fields that are produced by the eVTOL configurations – particularly the quad-copter – are subject to occasional transients during which the velocities close to the ground quite considerably exceed those which might be induced by any periodic variations in the flow. To a large extent, this observation supports the analysis of the structure of the outwash field that was presented in Section 12.2 by providing a quantitative link between the unsteadiness in the velocity field and the highly dynamic character of the vorticity distribution in parts of the flow.

(a) “Quad-copter” configuration



(b) “Lift-jet” configuration



(c) “Lift-cruise” configuration

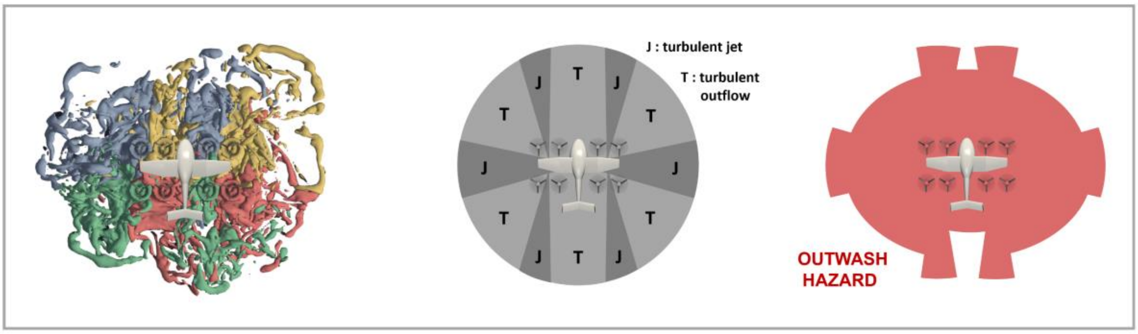


Figure 45: Schematic representation of the structure of the outwash field that is produced by various eVTOL configurations. At left, the outwash is represented via its vorticity distribution. At centre, this representation is simplified by segmenting the flow surrounding the vehicle into zones in which the outwash has a particular character. At right we suggest how our analysis might be converted into a practically-useful rendition of the hazard posed to bystanders by the outwash that is produced by each particular aircraft configuration. Top: “quad-copter” eVTOL configuration. Middle: “lift-jet” eVTOL configuration. Bottom: “lift-cruise” eVTOL configuration.

The middle plot in Figure 44 represents the same information as in the upper plot, but the data is referenced in this case to the properties of the outwash field of the helicopter with eVTOL-like disc loading. This figure provides the most robust characterisation of the effects of aircraft configuration on the velocities within the outwash field – essentially, each data point corresponds to the maximum value of the geometric amplification factor $k^c(r,\psi)$ for that particular aircraft configuration. In more prosaic terms, since the data for the eVTOL aircraft in this figure is referenced to that for a helicopter that has exactly the same disc loading, this figure confirms the fundamental role of the configuration of these aircraft in producing velocities within their outwash field that, in some cases, are significantly greater than those that would be expected within the outwash field that is created by an equivalent single-rotor helicopter even if it were to have the same disc loading.

The chart at the bottom of Figure 44 presents the same data yet again, but in this case with the plotted values referenced to the properties of the helicopter that has a disc loading that is more representative of conventional practice. This figure thus summarises the likely characteristics of the outwash field that might be produced by eVTOL aircraft as gauged relative to the characteristics of the conventional helicopters on which much of our understanding of the properties of the outwash field is based. As such, this figure encapsulates the compounded effects of disc loading and configuration on the strength of the outwash that might be produced by the vehicles that were studied relative to the strength of the outwash that would be produced by conventional helicopters in the same weight class.

Bearing in mind how the reference helicopter configurations were set up to represent the differences between conventional helicopter practice relative to the eVTOL aircraft in cluster C of Figure 13, the data supports strongly the contention that some of the eVTOL aircraft in that cluster might indeed produce a significantly stronger outwash than might be inferred from established helicopter practice.

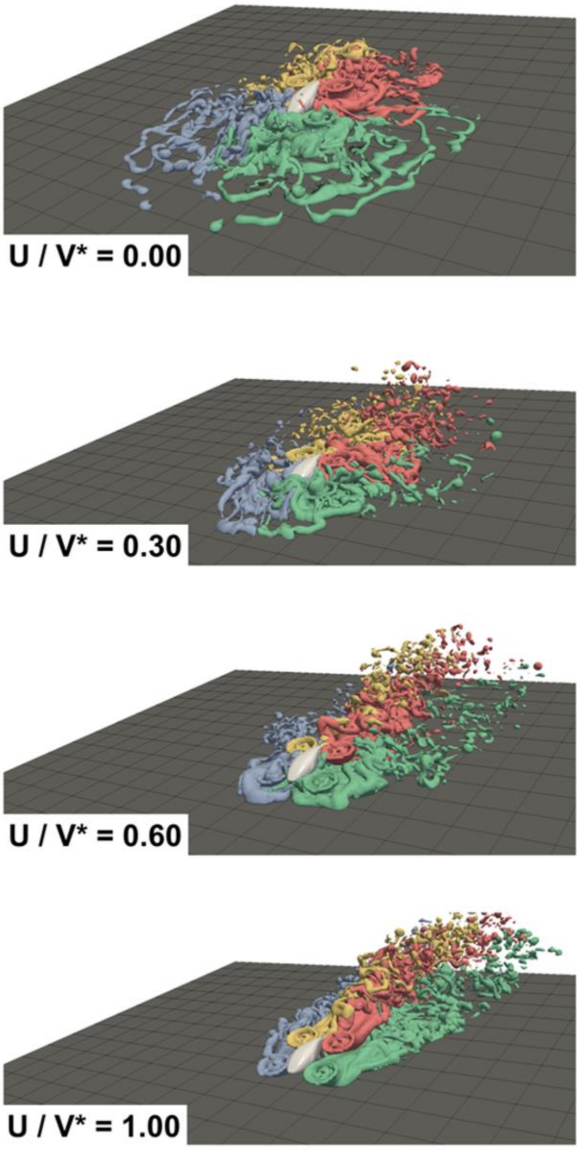


Figure 46: Structure of the flow produced by the "quad-copter" eVTOL configuration with the aircraft flying at various speeds (at height H = 0.50 R) above the ground.*

Indeed, the data for the configurations that were tested as part of this study suggest that the unsteadiness in the outwash field (as measured by the RMS velocity) that might be produced by some of these particular eVTOL aircraft might be capable of exceeding that within the outwash field of an equivalent conventional helicopter by a factor of between two and three. Similarly, the data suggests that the mean velocity in their outwash field might approach double that produced in the outwash of the equivalent conventional helicopter, and that the maximum velocities produced in their outwash field might transiently exceed those in the outwash of the equivalent conventional helicopter by a factor of between 2 and 2.5.

This data should certainly provide motivation to designers, operators and regulators alike to consider very carefully the recommendations made by the authors in Section 3 of this report.

The question then arises as to how this information might most usefully be exploited. To this end, Figure 45 suggests how information such as that produced by this study might be encapsulated in as useful a form as possible, particularly to the operators of these aircraft and also perhaps to the ground staff at the vertiports from which they might begin and end their journeys. It is difficult to dispute the fact that the plots of vorticity, reproduced for each aircraft at the left of the figure, are inherently complex, and arguably require specialist interpretation for maximum insight into the likely properties of the outwash field to be obtained.

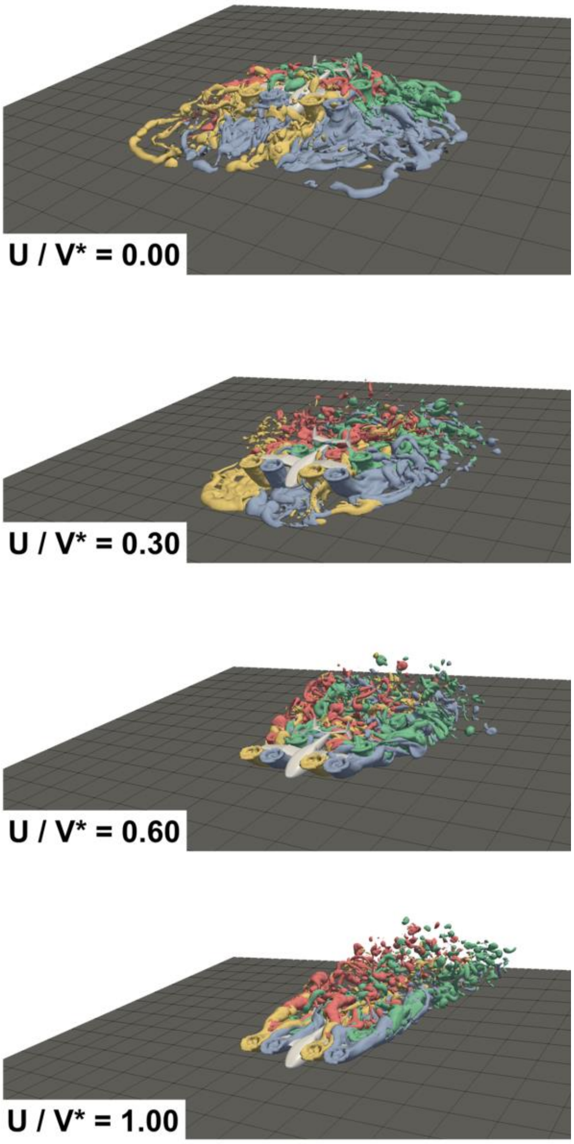


Figure 47: Structure of the flow produced by the "lift-cruise" eVTOL with the aircraft flying at various speeds (at height H = 0.50 R) above the ground.*

The figures at centre summarise the flow patterns in a highly schematic and condensed fashion, but incorporate the key idea that the outwash has a fundamentally different character in different sectors surrounding the aircraft. The effect on objects and personnel that might become immersed in the outwash will be different depending on the character of the flow - so, for instance, a shallow, fast-moving, but sheet-like flow might induce less upset than one which is deep and turbulent. Also encapsulated within this representation is that the shape of the outwash field is indexed to the axes of the aircraft, and not, for instance, and as is often assumed in helicopter operations (largely for simplicity, but perhaps also, as alluded to earlier, as a result of preconceptions as to the structure of the outwash field that is produced by even a simple, single-rotor helicopter) to those of the landing pad from which the aircraft is to operate. In other words, this representation takes into account the fact that, as the aircraft turns and manoeuvres near to the ground, the outwash field will itself rotate in order to re-orient itself with the axes of the aircraft.

The directionality and strength of the outwash field might then be summarised neatly for operational purposes by a representation along the lines of that shown at right, where the potential hazard posed by the outwash is summarised in similar fashion to that used in the civil airline industry to express to bystanders the hazards of approaching the intakes and exhausts of gas turbine engines. Whether such a marking needs to be affixed to the side of each and every eVTOL aircraft when they eventually come into service will of course be a matter for the operators and regulators to decide.

In the remainder of this analysis, we touch briefly on a range of other issues that have bearing on the character and strength of the outwash that eVTOL aircraft might produce when operating close to the ground. The exposition in many cases is rather brief and high-level, but the intent is principally to set down some pointers towards future areas of investigation where additional insights might readily help the designers, operators and regulators of eVTOL aircraft to understand more concretely the consequences of their decisions.

In the sections that follow, we first show how the structure of the outwash field changes when the aircraft moves from hover into forward flight, and make the observation that both the lateral extent of the wake and its extension back behind the aircraft might pose additional hazards in certain circumstances that might need to be considered. Given the observations made earlier in Section 9.6, to some extent the analysis of the characteristics of the outwash field that is produced in forward flight transfers also to the case where the aircraft is operating in windy conditions.

Secondly, we make small amends to the fact that we have so far presented very little information that deals with the interaction between the flow structures that are produced within the outwash field and the dynamics of the aircraft. Although clear signs of the close passage of the vorticity within the outwash field past the airframe or wings of the aircraft are apparent in many of the images of the flow that have been presented above, the analysis has not gone any further than postulating that these interactions might lead to a range of dynamic effects, some of which might be problematic from the point of view of the control or stability of the aircraft.

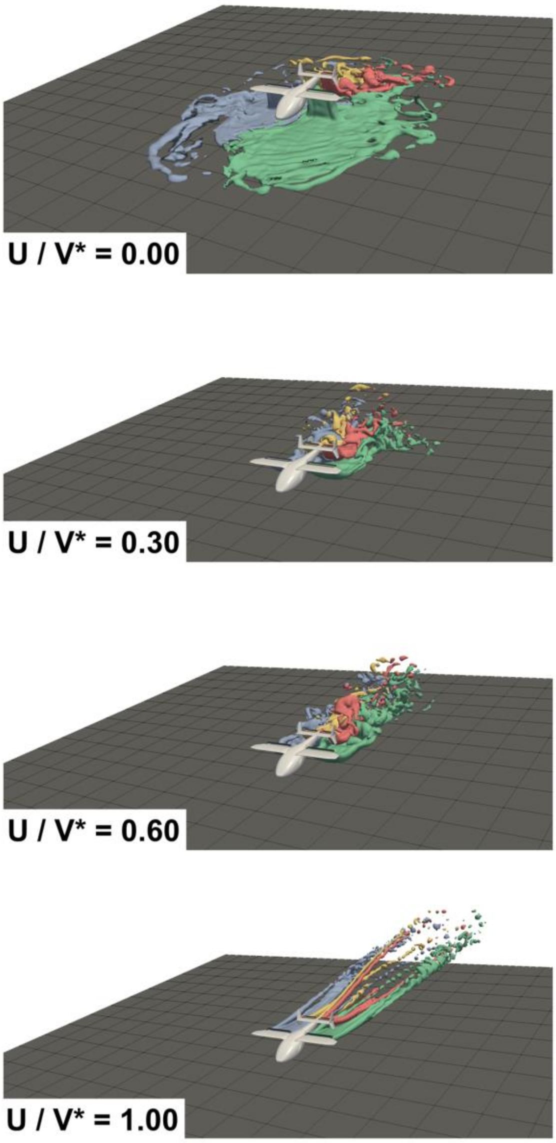


Figure 48: Structure of the flow produced by the "lift-jet" eVTOL configuration with the aircraft flying at various speeds (at height H = 0.50 R) above the ground.*

We thus present a short study on how the failure of one of the propulsors of an eVTOL aircraft with the geometry of the "lift-cruise" configuration might lead to quite significant transients in the outwash that it produces. Subsequently, we disturb the same aircraft in roll and examine how this perturbation to steady, level flight conditions - which have been assumed to hold throughout the remainder of this study - might influence the characteristics of the aircraft's outwash.

Finally, we show how the details of the configuration of the aircraft might influence the shape and structure of the outwash field. By examining the characteristics of two variations on the theme of the "lift-cruise" configuration, obtained by changing the positions relative to each other of the rotors on the airframe, we show that certain characteristic features of the outwash field, and particularly the directionality of the strong jet-like flows that tend to be formed along the confluence of the wakes of the individual propulsors, are amenable to modification through appropriate design. The way in which the flow responds to changes in the aircraft geometry is shown however to be contrary to what might be expected from overly simplistic, but nonetheless plausible rationalisations of the salient physics that are on a par with some of the heuristic models that are available within the literature. The analysis reinforces just how complex the underlying physics of the outwash and its dependence on the configuration of the aircraft might be in practice, and provides a salutary warning to the designers of such aircraft not to be too glib regarding the tools and arguments that they use to support their decisions.

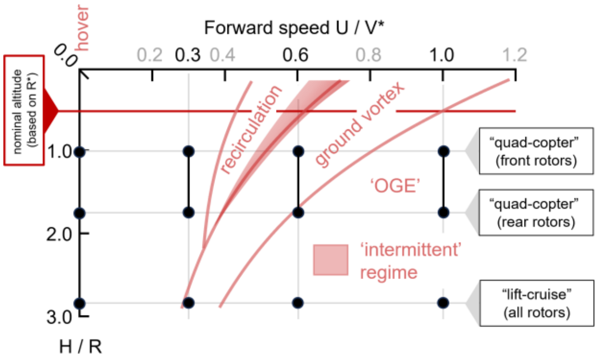


Figure 49: Curtiss diagram locating the effective height above the ground of the propulsors of the various eVTOL aircraft that were simulated. This representation can be used to predict the sequence of states that the wakes of the propulsors are likely to progress through as the forward speed of the aircraft is increased.

12.4 Effect of forward speed

Figure 46, Figure 47 and Figure 48 show the geometry of the outwash field that is produced by the various aircraft configurations when flying at a range of relatively low forward speeds across the ground. Data is presented for the aircraft flying at a height, H, above the ground of 0.50 R^* and with the aircraft moving horizontally with respect to the air at speeds, U, of 0, 0.3, 0.6 and 1.0 times the reference induced velocity V^*. This non-dimensional representation of the forward flight speed of the aircraft can be transformed into real units using Eq. (1) - once the size and mass of the aircraft and its density altitude are specified.

The overall characteristics of the flows that are created by the aircraft can be most readily understood if the states in which the rotors find themselves at any of the combinations of speed and height above the ground that were simulated are mapped onto the Curtiss diagram, introduced earlier in Section 11.5. Figure 49 shows how the diameter of each propulsor, together with the height at which the device is mounted on the airframe relative to the vehicle's datum, determines the state in which the propulsor's wake might be found with the aircraft flying through the air at any particular forward flight speed.

The small, high-mounted propulsors of the "lift-cruise" configuration operate at rather high effective height above the ground (as determined by their ratio H/R), for instance, compared to those of the "quad-rotor" configuration. The aerodynamics of the "quad-rotor" configuration is of course complicated by the fact that its front rotors operate at significantly lower effective height above the ground than its rear. Given the helicopter origins of the Curtiss diagram, extrapolation to the case of the "lift-jet" configuration with its non-circular, jet-like propulsors is potentially risky, but, given their slot-like character, the thrusters of these devices might be expected to operate with very high effective height above the ground. The omission of any direct effect within the Curtiss diagram of the aerodynamic interactions between the propulsors should also be borne in mind when interpreting the figures below.

Figure 46 shows how the structure of the wake that is produced by the "quad-copter" varies with forward speed above the ground. The wakes of the front rotors can be seen to evolve from producing an extended outwash out to the front of the vehicle when the aircraft is in hover, to eventually lifting clear of the ground and adopting the flattened, tubular structure that is typical of helicopter rotors in edgewise flight with the aircraft flying at the highest forward flight speeds. At intermediate speeds, the system transitions through a series of states, consistently with the changes implied by the Curtiss diagram, in which the wakes of the front rotors roll up on the ground plane in front of the aircraft to form the characteristic bow-shaped structures associated with the presence of a powerful ground vortex. The coalescence of the structures that are produced on either side of the vehicle to produce a combined structure that influences a fairly broad swath of the ground is a notable feature of the outwash field of this particular configuration at intermediate flight speeds.

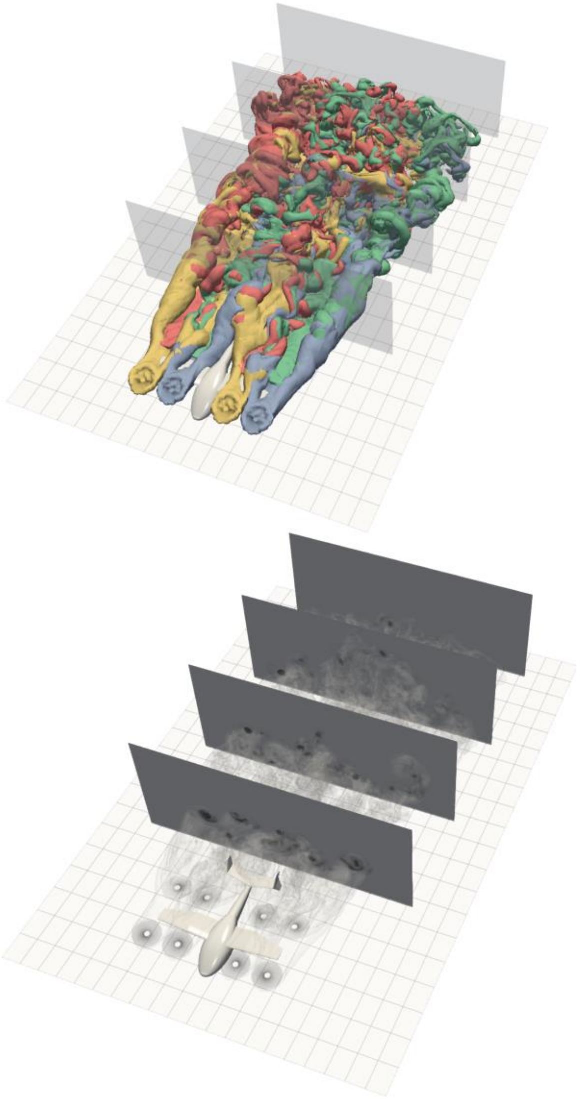


Figure 50: Visualisation of the vortices in the wake of the "lift-cruise" configuration when travelling across the ground at low altitude. The top diagram shows the overall structure of the wake that is produced by the vehicle; the bottom diagram shows the flow to be characterised by the presence of multiple, strong vortex cores, as illustrated by the darker patches on the various transverse cuts through the flow that are represented in the figure.

The outwash field of the "lift-cruise" configuration, shown in Figure 47, shows very similar changes in structure as the forward speed of the aircraft is increased from hover. The aerodynamic environment of the aircraft is complicated considerably by the presence of the wing and fuselage, however. The wing, in particular, finds itself immersed in the wakes of the forward rotors over much of the speed range, and the interaction of the rear rotors with the ground tends to produce a tall 'rooster tail' of intensely chaotic flow behind the aircraft that has the potential to interfere with the empennage of the aircraft. The history of VTOL aircraft is replete with many examples where interactions between the wakes of the propulsors and the airframe have led to serious handling qualities issues with the aircraft operating at low forward speeds just above the ground, and the aerodynamic behaviour of the particular configuration that was tested here illustrates very clearly how the presence of the ground can have a strong effect in driving some of the most powerful vortical features up close to the airframe where they can readily interact with the rear fuselage or tail surfaces of the aircraft.

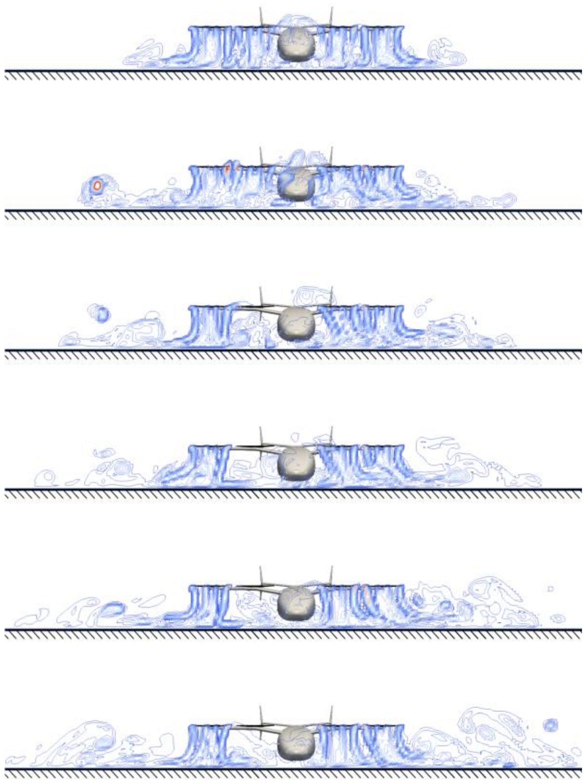


Figure 51: Cross-sections through the flow (at the location of the front rotors) produced by the "lift-cruise" configuration at various instants following failure of the inboard propulsor located forward of the starboard wing. Time increases from top to bottom in the diagram. The aircraft is initially hovering at height H = 0.25 R above the ground.*

If the Curtiss diagram is indeed applicable to the "lift-jet" configuration, then the very high effective height of its propulsors would be expected to lead to the structure of their wakes changing very abruptly, and at relatively low flight speed compared to the other configurations that were tested, from giving the outwash field a hover-like structure at low forward speed to the flow adopting the configuration that it would have in high-speed forward flight when the aircraft is effectively clear of the influence of the ground. The information presented in Figure 48 would seem to be consistent with this interpretation – indeed, the formation of any appreciable ground vortex would appear to be contained within the interval during which the aircraft accelerates from hover through to about $0.3\,V^*$, by which stage the wakes of the propulsors have already lifted clear of the ground.

Finally, Figure 50 provides a reminder that the wakes that are produced by multi-rotor aircraft can extend in powerful fashion for appreciable distances back behind the aircraft. This is particularly the case when the vehicle is operated close to the ground, since the solid surface below the aircraft then constrains the vorticity in the wake from moving down into the flow below the aircraft as readily as it would were the aircraft to be operated in free air. The structure of the 'wake turbulence' behind a multi-rotor vehicle can be extremely complex, as is evident from the lower plot in the figure, which shows the flow on any particular slice downstream of the aircraft to contain a number of powerful, and, in fact, highly dynamic vortex cores. Over the years, the VTOL community seems to have consistently under-appreciated the dangers to following aircraft that might be posed by the wake that is streamed out behind conventional helicopters[56,57], and it might be the case that eVTOL aircraft, with their characteristically more complex aerodynamics and higher disc loading, may pose an even more pressing problem.

12.5 Transient conditions

Figure 51 and Figure 52 show how the structure of the outwash field might alter transiently in response to a failure of one of the propulsors of the simulated representative of the "lift-cruise" eVTOL configuration. Figure 51 represents the dynamics of the flow with the aircraft hovering at a height of $0.25\,R^*$above the ground, and Figure 52 shows similar information but with the aircraft hovering at a height of $0.50\,R^*$. In both figures, a series of cross sections through the vorticity distribution in the plane of the front rotors is portrayed as a sequence of contour plots of the flow at subsequent intervals of time following the failure of the forward inboard rotor on the starboard wing. The failure of the rotor is simulated very simply by reducing its rotational speed instantaneously to zero, and it is also important to point out that no account of the subsequent dynamics of the airframe was made during the simulation, nor were the settings on any of the other rotors changed to compensate for the loss of thrust on the rotor that had failed.

Even in these simplified circumstances, the simulations reveal some interesting effects. In both cases that were simulated, an initial transient involves the 'flushing' of the vorticity created at earlier times by the failed rotor out from under the vehicle and into the outwash field, and the remnants of this vorticity can be seen in the earliest snapshots of the flow as it evolves. Indeed, some of the most concentrated features in the outflow during the earlier stages of the response of the system to the failure appear to be induced by the ejection of the vorticity from the failed rotor out into the flow surrounding the vehicle.

The wakes that are produced by the still-functioning rotors of the system then begin to change their geometry in response to the failure. The accommodation that takes place in the wake of the inboard rotor in front of the wing on the opposing side of the aircraft is most obvious. This is understandable given that this rotor now finds itself absent of its very direct interaction with the flow from the rotor that has just failed. During the course of a very rapid transient, the flow below the aircraft loses its lateral symmetry, and the two counter-rotating vortices that form the fountain flow below the fuselage of the fully-functional aircraft are replaced by a jet of flow that travels from port to starboard underneath the belly of the vehicle. The effects of the failure of the rotor are felt on all the other propulsors of the system as the configurations of their wakes adapt and accommodate to each other during this transient, and eventually the system reaches a new state that is consistent with the disappearance of virtually all aerodynamic interaction with the failed rotor.

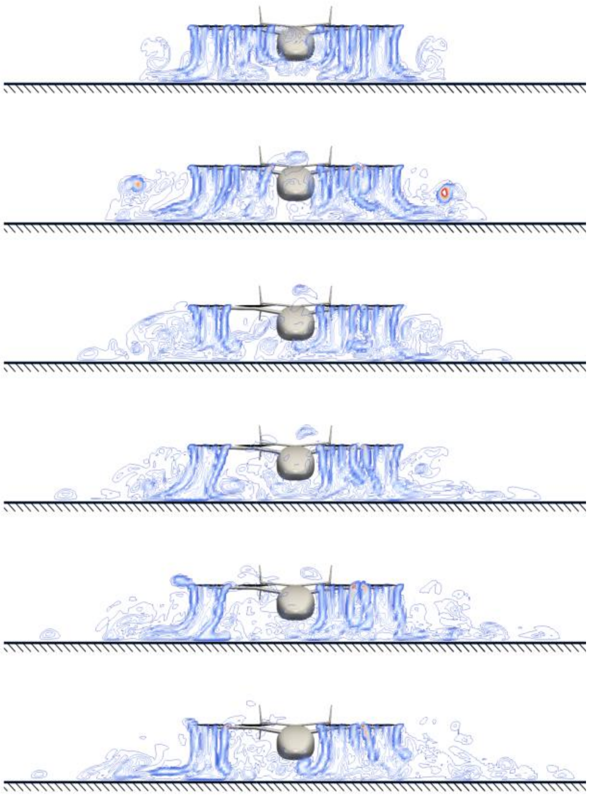


Figure 52: Cross-sections through the flow (at the location of the front rotors) produced by the "lift-cruise" configuration at various instants following failure of the inboard propulsor located forward of the starboard wing. Time increases from top to bottom in the diagram. The aircraft is initially hovering at height H = 0.50 R above the ground.*

This case illustrates very well how the failure of an isolated element of a very compact aircraft with multiple propulsors can have system-wide consequences. The propagation of the effects of the failure throughout the system is mediated by the very strong aerodynamic interactions between the various components of the system, and the changing form of this interaction is clearly evident as the wakes of the propulsors evolve in the aftermath of the failure. Contrasting the detail of the examples presented in Figure 51 and Figure 52 for the aircraft at different heights above the ground suggests that a critical height might exist at which these interactions have maximal effect on the dynamics of the aircraft subsequently to the failure of one of its propulsion systems, and certainly the results presented here suggest that the

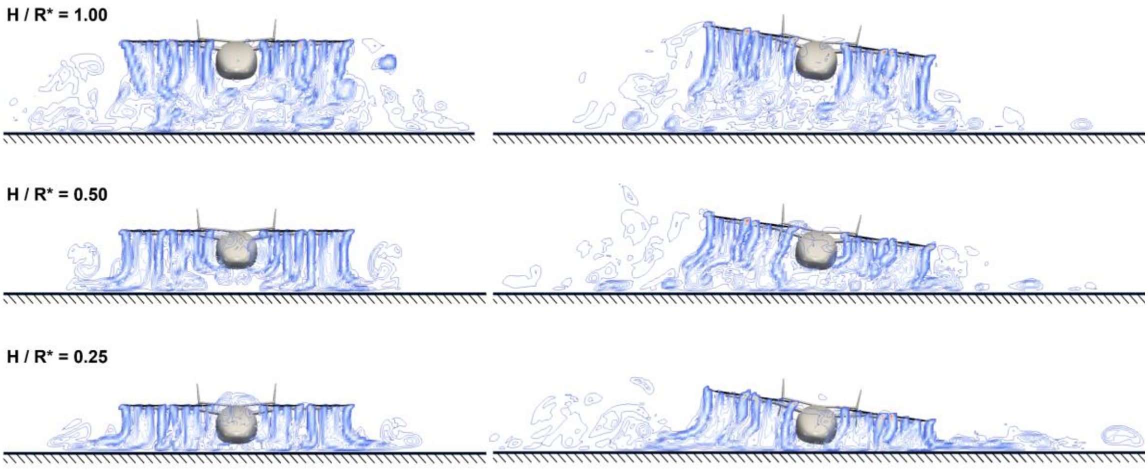


Figure 53: Cross-sections through the flow (at the location of the front rotors) produced by the "lift-cruise" configuration when the vehicle is simulated at various heights of above the ground. Left: with the aircraft in hover and its wings level. Right: with the aircraft in hover but rolled eight degrees to port.

designers of eVTOL aircraft would do well to consider the effect of height above the ground in terms of the ability of their particular vehicle to recover from this or similar such events.

A second example of the possible behaviour that might be associated with multi-propulsor aircraft when operating close to the ground under transient conditions is shown in Figure 53. In this figure, the aerodynamics of the representative of the "lift-cruise" eVTOL configuration is compared with the vehicle at three different heights above the ground following transient entry of the aircraft into an eight-degree bank to port. As in Figure 51 and Figure 52, the flow is visualised as a series of contour maps showing the vorticity distribution on a vertical slice through the outwash field on the plane containing the front rotors of the vehicle.

It is clear that the height of the vehicle above the ground influences quite considerably how the outwash below the vehicle evolves following the transient. As before, the characterisation of the structure of the wake of an isolated propulsor in terms of the progression of its inherent vortical instabilities, as described earlier in Section 11.3, is useful in explaining the physics. With the aircraft at the greatest altitude that is illustrated in the figure, the vehicle is insulated from the ground by a thick and relatively turbulent layer of air. With the aircraft in this particular state, perturbation of the bank angle of the aircraft does little to change the form of the interaction of the individual wakes of its propulsors with the ground. Although the structure of the outwash from the banked aircraft differs considerably in detail from the outwash that is produced by the aircraft when flying at the same height above the ground but with its wings level, the outwash on both sides of the vehicle is still essentially turbulent in character.

As the height of the aircraft above the ground is reduced, however, a change in the bank angle of the aircraft becomes capable of inducing the wakes of the rotors on either side of the aircraft to exist in different states of disorder by the time that they reach the ground. This is most clearly obvious in the bottom set of figures, where the wakes of the rotors on the starboard wing at the point of their interaction with the ground have been induced into a far more disordered state than the wakes of the rotors on the port wing. The consequence of this is that the outwash to the port side of the aircraft consists of a thin, rapidly-moving, sheet-like flow, while the outwash to the starboard side of the

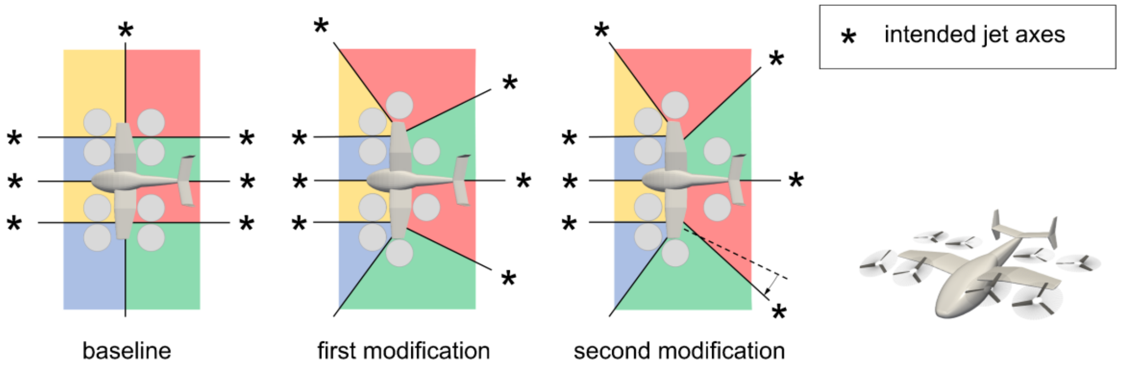


Figure 54: Schematic that suggests a simple heuristic method for determining how the flow within the outwash field might respond to changes in the juxtaposition of the rotors of the vehicle. In the example shown, the method is used to contrast the expected characteristics of various representatives of the "lift-cruise" eVTOL configuration.

aircraft consists of a deep layer of turbulent vorticity that spreads out more slowly into the vehicle's surroundings.

This behaviour may seem rather counterintuitive to the reader who might expect the most intense outwash to be formed on the side of the aircraft towards which the downwash from the rotors appears to be directed. In relying on intuition in these complex circumstances, however, it is always important to take very carefully into account the inherent nonlinearity of the flow surrounding the vehicle, and in particular the dominant role of vortical instability in governing the structure of the wakes of the vehicle's propulsors as they interact with each other and with the ground during the process of formation of the outwash field.

12.6 Tailoring the structure of the outwash field

From the aircraft designers' point of view, it would be very useful to have to hand a set of heuristics that would allow the likely structure of the outwash field that might be produced by an aircraft with any notional configuration to be predicted with accuracy and confidence, and, preferably, with very little computational effort. These heuristics could be used during the early stages of conceptualisation of the vehicle, for instance to tailor the properties of the outwash field to reduce the likely impact that their particular choice of aircraft design might have on its surroundings once it enters service. The economic benefits of such an approach are compelling, enabling the aircraft for instance to be designed from the outset to operate successfully from a broader range of vertiports than would otherwise be the case. As mentioned in Section 5.4, such a body of semi-empirical design guidance was developed quite extensively from the 1940s onwards within the jet-lift community, where it was applied, admittedly with varying degrees of success, to predicting the characteristics of the outwash of vehicles such as the Harrier and F-35. Certainly the creation of an analogous body of work within the eVTOL domain would be of considerable utility, and the success with which the relatively abstract analysis of the properties of propulsor wakes presented in Section 11 can be applied to understanding some of the features of the outwash that is created by multi-propulsor vehicles, especially those with as complex a configuration as those examined here, is testimony to the value of well-structured abstraction of the relevant physical effects into an appropriate semi-heuristic framework.

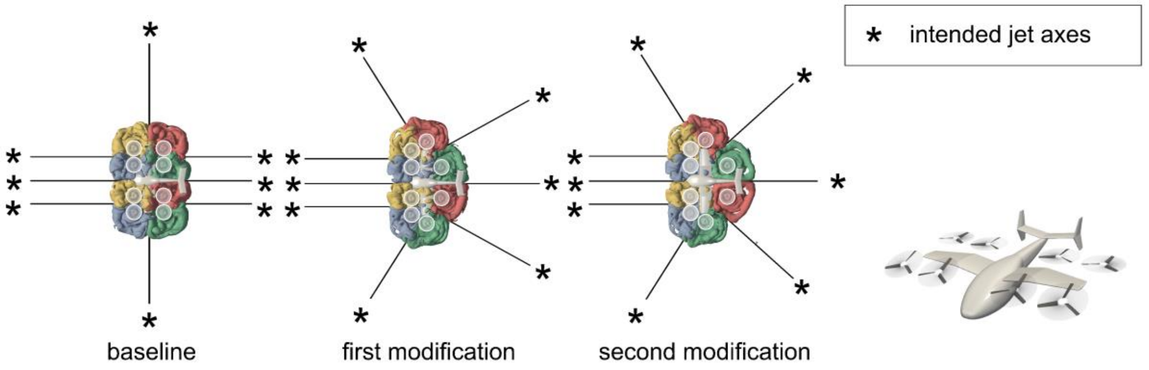


Figure 55: Visualisations of the outwash field at an early stage of its evolution, prior to the onset of symmetry breaking within the flow, suggest that the simple heuristic method for locating the jet like flows within the outwash field might have merit.

It is perhaps important though that the difficulties and effort that will be involved in producing such a body of design support are not trivialised or downplayed, and the following short example serves both to expose the dangers in adopting overly simplistic reasoning as to the likely behaviour of the outwash field in response to changes in the configuration of the aircraft, as well as perhaps to reinforce, if such reinforcement is necessary, how complex the flows that are produced by eVTOL aircraft actually are, particularly when these vehicles are operated close to the ground.

As shown in Section 11.4.2, one of the principal features of the outwash field that is generated by a multi-propulsor aircraft is the presence of strong, outwards-directed jets that are located along the confluences between the flows that are created by the individual propulsors for the vehicle. The velocities that are created within these jets are arguably the most pernicious features of the outwash when the interaction of the aircraft with its surroundings is considered. The question thus arises whether the directionality of the jets can be altered simply by changing the design of the aircraft - for instance by changing the relative juxtaposition of the vehicle's propulsors. In the case of the "lift-cruise" configuration, for instance, can the jet flow outwards along the span of the wing, seen in the plots in Section 12.3, be replaced by a series of more benign flows, simply by relocating the outboard rotors of the vehicle?

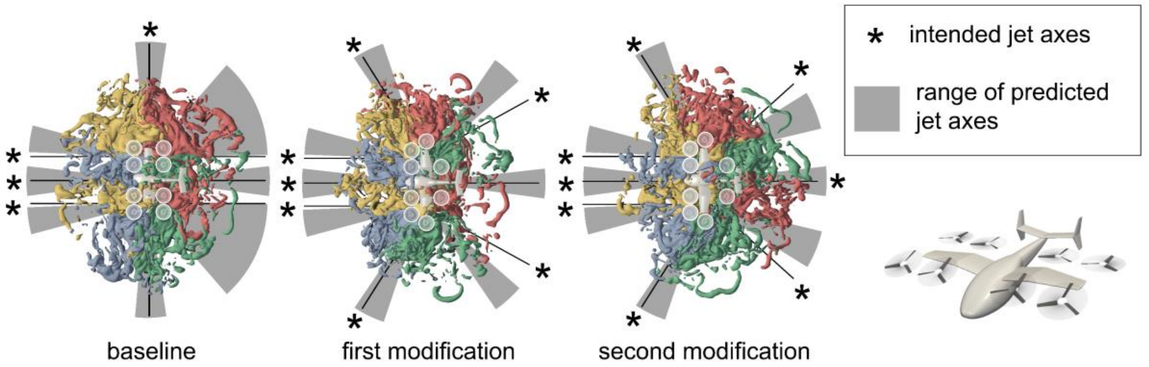


Figure 56: Visualisations of the outwash field, once the flow has matured, showing that the simple heuristic method is only partially successful in predicting the location of the jet-like outflows that are located at the confluences of the wakes that are generated by the individual rotors of the configuration.

Figure 54 illustrates, in schematic form, the simple logic that might be used to justify such a change in the configuration of the aircraft. If all the rotors create the same thrust, then it might be argued perfectly rationally that the sectors of the flow that are influenced by each rotor would be expected to conform to the partition of the ground plane that is shown - where each point on the ground plane is immersed in the flow that is created by the rotor that is geometrically the closest to it. This heuristic, applied to two different potential design modifications, is shown in the figure. In the first modification, the outermost propulsor located behind the wing is moved outwards and forwards in an attempt to replace the spanwise jet with a structure that is more closely aligned with the longitudinal axis of the aircraft. By the same logic, this modification would appear also to rotate the jet that is produced at the confluence between the wakes of the rotors behind the wing so that it points further outboard. This rotation is potentially advantageous when the interaction of the outwash with the empennage of the aircraft is considered, so, in the second instance, the innermost rotors located behind the wing are moved further aft in an attempt to rotate the axis of this jet even further outboard.

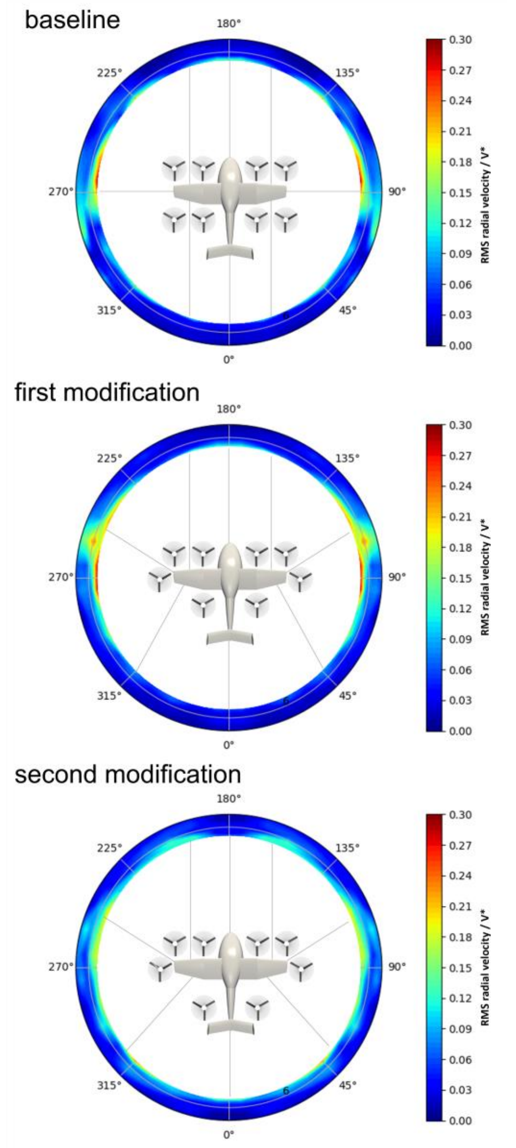


Figure 57: RMS velocities in the radial flow at a distance of 5.5 R from the "lift-cruise" configuration, showing the effect of changing the rotor location on the direction of the jets that are produced at the confluences of the individual rotor wakes.*

The series of visualisations of the flow within the earliest stages of its evolution that are presented in Figure 55 appear to support the validity of these modifications. Prior to the onset of the symmetry breaking within the flow that is driven by its inherent vortical instability (see Section 12.2), the location of the confluences of the wakes that are produced by the various rotors follows very closely the tessellation of the ground plane shown in Figure 54. This situation does not persist, however, as shown in Figure 56, where snapshots of the more completely developed flows that are generated by the three different configurations are contrasted. Figure 57 lends additional insight into the effect of changing the aircraft's geometry by presenting plots of the RMS velocity on a cylindrical measurement surface that is located in this case at a distance of 5.5 R^* from the centre of the vehicle. While the spanwise jet appears indeed to have been replaced by a structure that is significantly inclined with respect to the axis of the corresponding outflow of the baseline aircraft, and the inboard jet located behind the wing is most definitely rotated outboard away from potential interference with the empennage, the simple heuristic does not account particularly well for a residual bias of the jets which causes them in almost all cases to be directed somewhat further outboard than might be expected. Indeed, a distinct flaw in the logic used to locate the propulsors is particularly apparent - the response of the system to changing the position of the innermost rotors behind the wing appears to be entirely counter to what might have been expected from the simple reasoning that was used to support the proposed changes to the aircraft configuration in the first place! If anything, the results presented here are a salutary lesson that one can only proceed so far when attempting to micro-manage a flow that is inherently nonlinear and unstable.

13 Closing remarks

Such are the complexities of the flows that are created by these machines that there will potentially always be a role for detailed numerical analysis, supported where necessary by careful experimental measurements, both at model scale and in the real world. As remarked earlier in this report, the present study has merely scratched the surface of a topic that embodies fluid dynamics that is as intricate and beautiful as encountered anywhere else within the engineering domain, and involves aircraft that in many cases are extremely complex both in terms of their configuration and in terms of their intended mode of operation. It is hoped that the information that is presented in this study will be of utility to the designers, operators and regulators of eVTOL aircraft alike, and will contribute to our understanding of the complexities that need to be faced up to when designing an infrastructure that is safe enough for the travelling public to be able to use with the confidence that they deserve.

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