Do eVTOL Aircraft create an inherently more problematic Downwash than Conventional Helicopters?

R.E. Brown

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DO eVTOL AIRCRAFT CREATE AN INHERENTLY MORE PROBLEMATIC DOWNWASH THAN CONVENTIONAL HELICOPTERS?

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Extensive worldwide interest in the rotorcraft industry currently exists in developing small, lightweight, electrically-propelled multi-rotor craft, typically capable of carrying four to six passengers on short-range intra-urban missions, for instance as part of a passenger ferry service between an airport and a downtown commuter hub. The potential for the flows generated by helicopter rotors to create significant upset in the vehicle's surroundings has long been appreciated by the rotorcraft community, yet very little has been written, until recently, about the structure of the downwash field that these new eVTOL aircraft will create, and how this field might interact with the ground during landing and take-off. A new numerical study suggests that the interactions between the multiple wakes of the rotors of some of these vehicles could amplify and modify key features of the field, especially when it interacts with the ground and turns to outwash. Indeed, the study suggests that the flow out across the ground that is generated by these vehicles could potentially be very different in character and strength to that which is produced by conventional helicopters. We discuss some of the potential implications of these findings for the developers and operators of these new aircraft, as well as for the designers of the vertiports at which they will begin and end their journeys.

1 INTRODUCTION

That helicopters create a powerful downwash field below their rotors is a well-known fact. When landing or taking off, the vehicle is operating at low forward speed, and the downwash below the rotors is generally at its strongest. When a helicopter operates at heights above the ground that are comparable to its rotor diameter, or lower, the interaction with the surface below causes the downwash to expand out across the ground as a layer of rapidly-moving air.

Even in the case of a helicopter with relatively conventional configuration, the structure of this outwash field can become very complex from a fluid dynamic perspective. Zones of recirculation, and even upwash, can exist below the fuselage and rotor, and the velocity within the outwash field can vary appreciably with distance from the rotor, and with azimuth with respect to the heading of the helicopter. It is known too that the fundamental topology of the outwash field changes significantly with the forward speed of the helicopter across the ground, as well as in the presence of winds and atmospheric turbulence.

Figure 1
Two notional eVTOL aircraft operating from a rooftop vertiport located deep within an urban area. (Image source: Embraer.)

Limited experience with more complex rotorcraft configurations, such as tilt-rotors and tandem-rotor helicopters, hints at a range of additional features. Upwards-directed fountain-flows at the confluence of the wakes below the centreline of a tilt-rotor aircraft, for instance, can create appreciable forces on the airframe, both steady and unsteady, and jets of particularly high-velocity flow can be created just above the ground along the longitudinal axis of the vehicle[1].

The flow created by tandem rotors is arguably even more complex: the overlap between the rotors creates a zone of intense vortical mixing, and this manifests in a highly unsteady flow that jets laterally outwards from the helicopter in a thickened layer just above the ground. An interesting feature of this outwards jet is that it is generally stronger on one side of the helicopter than the other[2], calling into question some of the more elementary predictive models, particularly those based on simple momentum considerations.

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Many current concepts for eVTOL aircraft have been designed to have far more complex configuration than has traditionally been the case in conventional helicopter practice. Many of these designs have four, six, eight, or even more rotors, arranged in various juxtapositions along the wings and tail surfaces to exploit the advantages of Distributed Electric Propulsion, or clustered in various ways around a central fuselage or passenger-carrying pod.

This radical departure from conventional helicopter experience, upon which much of our understanding of the characteristics and behaviour of the outwash field is founded, suggests that a more complete exploration of the likely characteristics of the outwash field that will be generated by these new configurations would be prudent - if only to obviate any suspicions that the downwash that is produced by these vehicles will pose an unforeseen danger to the passengers and personnel with which they will come into contact during their daily operation (see Fig. 1).

This paper sets out some of our thoughts on how the rotorcraft community might come to a better understanding of the downwash/outwash properties of multi-rotor eVTOL-like aircraft, and then use this new insight to ensure the continued safety of the transport infrastructure when these vehicles come into service. Our analysis is based largely on the findings of a numerical investigation into the outwash characteristics of a range of generic eVTOL-like aircraft, the results of which are to be published very shortly[5].

2 A NEW STUDY

A particular concern is that the outwash that is produced by this new class of vehicles might be so different in character to that which is produced by conventional helicopters as to call into question established wisdom, particularly where this is founded on helicopter experience alone. The possibility exists that some of the standard approaches and techniques that have been developed over decades of experience with more conventional VTOL machines might need to be re-visited in the light of the complexity of the flows that eVTOL aircraft will produce when operated close to the ground.

These concerns manifest in particularly practical terms, for instance, in the design of the vertiports at which these aircraft will begin and end their journeys. In this particular domain, the concern might very rationally be that constructs such as the ‘minimum enclosing circle’ (or ‘D-value’), that are universally used as a measure of the range out to which a helicopter might have significant impact on its surroundings[3][4], may need revision in the light of a better understanding of the aerodynamic properties of this new class of vehicles.

To provide some concrete information that could be used to resolve some of these issues, the aerodynamics of a small sample of generic aircraft configurations, all with features representative of current eVTOL design practice, were simulated computationally[5]. The investigation was able to shed significant light on the physics that is primarily responsible for the particular characteristics of the outwash that vehicles with eVTOL-like configuration will generate when operating close to the ground. Indeed, the study was able to show that the interactions between the wakes of the rotors are the prime reason why aircraft with eVTOL-like configuration tend to produce an outwash field that is particularly complex and spatially non-uniform in structure - as well as, in some cases, one that is quite considerably stronger than the outwash that is created by an appropriately-defined, equivalent, conventional helicopter[5].

The intent of the present paper is to extend slightly beyond these findings, and to discuss how we might proceed in their light - firstly, to ensure that we understand the potential dangers that might be posed by the downwash/outwash that is produced by eVTOL-type vehicles, when the class is defined relatively broadly, and, secondly, to ensure that we have to hand the requisite tools to ameliorate the effects of any particular vehicle’s downwash/outwash on its surroundings - if that indeed turns out to be necessary.

3 HELICOPTER EXPERIENCE

Our present understanding of the effects of helicopter outwash is generally formulated around the idea that the rotors, in producing thrust, generate a downwash that, once it comes into contact with the ground, is turned outwards to form a layer of fast-moving air that spreads out and away across the surface[1][6]. The kinematics of the flow within this layer is generally described in terms of a ‘mean flow’ ground-jet, on top of which a fluctuating velocity component is superimposed. There are serious physical deficiencies in this conceptualisation of the fluid dynamics of rotor interaction with the ground, but this ‘momentum-jet’ model forms a useful foundation from which to expand our understanding of the outwash field that is produced by a system of rotors when they interact aerodynamically with the ground.

Figure 2 shows a schematic, constructed from within the momentum-jet paradigm, of the geometry of the outflow field for an isolated rotor, as well as for two rather widely-spaced rotors - as characteristic, for instance, of tilt-rotor aircraft. The outwash field of the isolated rotor is radially-symmetric, and decays rapidly with distance from the rotor. In this simple representation of the twin-rotor case, the confluence of the outwash fields that are produced independently by the rotors results in a re-direction of the flow upwards and outwards to form a localised region in the

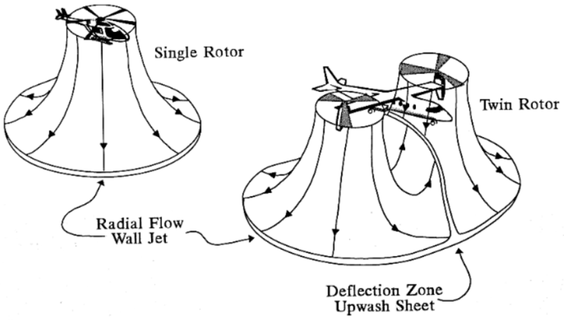

Figure 2
Schematic showing the geometry of the downwash/outwash field for single-rotor and tilt-rotor aircraft[1].

flow where the outwash velocities are significantly higher than elsewhere.

Understanding the orientation and strength of these regions of enhanced outflow is essential if an appreciation is to be gained of the likely dangers posed by the outwash field to operations on the ground - especially if this appreciation is to go beyond a simple order-of-magnitude estimate in terms of the disc loading of the rotors of the system. Extension of the simple geometric arguments that are summarised in Fig. 2 to aircraft that have more complex configurations, is not particularly straightforward, however.

The effect of winds and the forward motion of the vehicle in breaking the symmetries inherent in the simple representations of the outwash fields shown in Fig. 2 is also not particularly clearly understood. It is known that the topology of the outwash field that is generated by an isolated rotor proceeds through a series of transitions as the velocity of the rotor relative to the surrounding airflow is increased[7][8] (see Fig. 3). At the lowest forward speeds, the ground flow tends to re-circulate upwards and through the rotor disc. At higher forward speeds, this recirculatory flow condenses into a distinct, bow-shaped vortical structure that precedes the rotor through the air. At higher speeds still, the rotor wake lifts clear of the ground and forms a pair of counter-rotating “trailing vortices” in the flow behind the rotor. Any vestiges of the bow-shaped vortex on the ground tend to interact with these trailing structures in a highly unsteady manner, but a forward speed is eventually reached where this structure disappears entirely and the effect of the ground on the rotor weakens appreciably.

4 NUMERICAL INSIGHTS

Not much has been written, at least up to the present, about how our knowledge of the behaviour of isolated helicopter rotors extends to systems with multiple rotors, and particularly to those systems where the rotors are so closely spaced that their mutual aerodynamic interaction plays a significant part in defining the structure and dynamics of the wake of the aircraft.

Figure 4 reveals some of the aerodynamic features that appear to be reasonably generic to the outwash field that is produced by eVTOL-like aircraft when they are operated close to the ground. The quad-rotor configuration of this aircraft is broadly representative of some aspects of current eVTOL design practice, but it is important to realise that both the geometry of this aircraft and its flight condition have been set up solely to illustrate some of the key features in the outwash that is produced by a multi-rotor aircraft, rather than to represent the characteristics of any particular design that is currently under development. It is particularly important to bear in mind too that the specifics of the aerodynamic behaviour of systems such as this are known to be very sensitive to the details of the aircraft’s configuration. Thus, in interpreting the analysis that is presented below, care should be taken to distinguish those elements that are generic from those that are specific to the particular configuration that has been modelled.

The aerodynamics of the aircraft has been simulated using Sophrodyne’s SophIA-C computational model, which is based on the numerical formalism of the Vorticity Transport Model[10]. The key feature of this approach is that the vortical structures that are produced by the lifting elements of the aircraft are particularly well preserved as they convect away into the flow, allowing the effects of aerodynamic interaction and the associated changes in the structure and form of the aircraft’s wake to be clearly identified. Indeed, this vortical approach provides detailed insights into the structure of the flow, as it evolves, that are very difficult to capture using more traditional CFD-based approaches.

The simulation has the aircraft flying at low forward speed and with an angle of incidence to the flow that has been set up to represent flight conditions that might be encountered, for instance, while manoeuvring onto a landing spot. The flow is visualised as a set of surfaces on which the vorticity produced by the rotors has a constant value, and this value is set low enough to expose the broad extent of the wake in

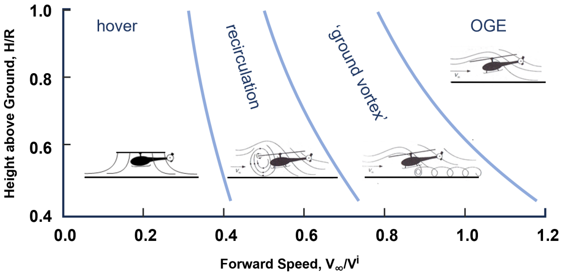

Figure 3
Curtiss’s diagram showing how the flow below the rotor can exist in one of several states, depending on the altitude and speed of the system above the ground.
(Image adapted from Refs. 7 and 9.)

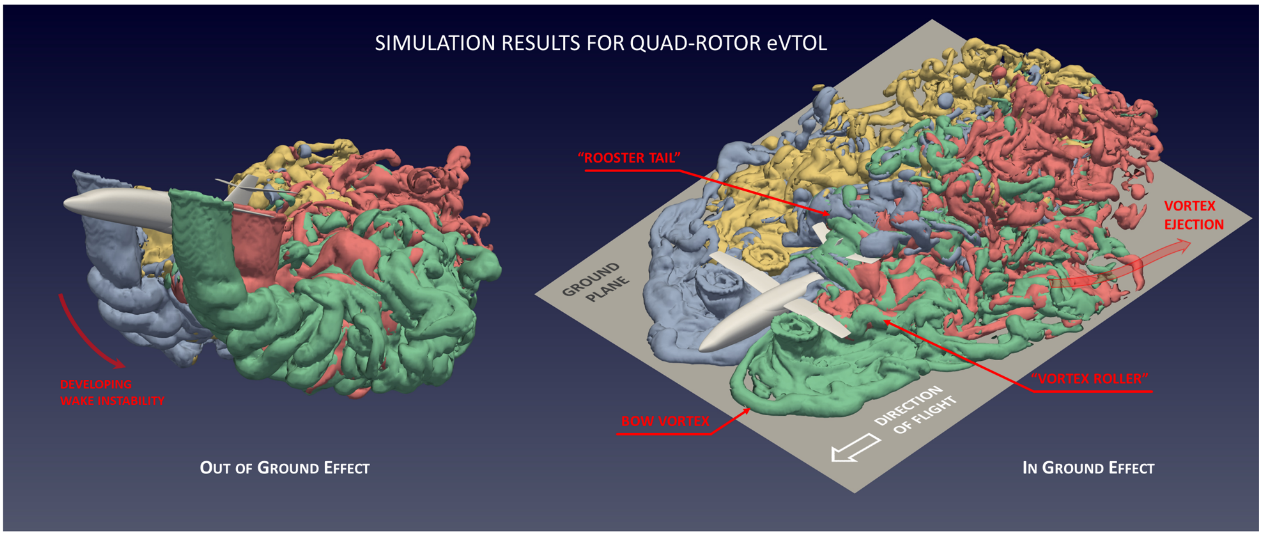

Figure 4
SophIA-C simulation of the aerodynamics of a quad-rotor eVTOL aircraft out of ground effect (left) and in ground effect (right).

preference to the more detailed features of the flow. The wakes produced by each of the rotors have been coloured separately to provide additional insight into the salient physics. A representation of the fuselage, empennage and wing of the aircraft is included in the figures simply to aid interpretation, but was not part of the calculation in this particular case - which was set up to examine the flow field that was produced by just the four rotors of the system on their own.

The diagram at the left of Fig. 4 represents the flow field that is produced by the rotors when the vehicle is flying in free air. The diagram at right represents the same system when the aircraft is flying at a height of about one rotor diameter above a flat, smooth ground plane. The rotors are non-articulated, as is common eVTOL practice, and the system is trimmed using the collective pitch of the rotors to achieve the same overall lift in both cases. Each image is a snapshot of the flow at a particular instant, selected to show some of the most salient, but not necessarily the most persistent, aspects of the aerodynamics of the system. (Indeed the movie showing the evolution of the flow over time provides the clearest picture of events but, for obvious reasons, is impossible to reproduce here.)

When in free air, the wakes from the four rotors descend into the flow below the aircraft, maintaining their tubular structure (as is assumed by most classical expositions of the aerodynamics of rotor wakes) for quite some considerable distance below the vehicle. What is often less well-appreciated in the classical literature, however, is that the wakes are subject to a natural vortical instability.

The effects of this instability build up in the flow, eventually disrupting the orderly development of the wakes of each of the propulsors and transforming them into the disordered tangle of vorticity that can be seen in Fig. 4. In free air, this process generally takes place far enough away from the aircraft to have little direct effect on its aerodynamics - unless the aircraft begins to descend, in which case the aircraft can become subject to an extremely dangerous and more global wake instability that eventually leads to the onset of the Vortex Ring State[11].

With the aircraft closer to the ground, the vortices persist near the vehicle for much longer, and the aerodynamics is thus the result of the convection of individual vortex filaments out across the ground plane as influenced by their inherent instability as they interact with each other and the ground itself. The image at right in Fig. 4, with the aircraft in slow forward flight just above the ground plane, shows the flow field surrounding the aircraft to be extremely complex. Perhaps less clear from a cursory inspection is that there is much order and structure within the tangle of vortical filaments that is produced by the four rotors of the aircraft.

As might be expected given the forward speed of the simulation, the prime feature of the flow is the pair of horseshoe-shaped “bow vortices” that are formed by the coalescence of individual tip vortices into more intense structures located just above the ground plane and somewhat forward of the two foremost rotors. The leading edges of these vortices tend to remain relatively stable in their position, but their trailing arms are much more dynamic. Indeed, these structures tend to meander, spiral and contort as they stream backwards into the wake behind the vehicle.

The two rear rotors have a much harder time in producing similarly coherent structures - instead the interaction with the front rotors causes these rotors each to produce an array of powerful, laterally-oriented structures called “vortex rollers”. These composite structures do not tend to propagate downwards towards the ground, but instead spend most of their time at more or less the same height above the ground as the rear rotors. The angle at which these vortical structures project themselves into the flow seems to be particularly conducive to intermittent interaction with the trailing arms of the bow vortices created by the front rotors. Indeed, the mixing of the vorticity that is associated with this interaction seems to be the cause of intense, but localised, lateral ejections of vorticity from the wake, and these are indeed the analogues of the jetting phenomenon that is referred to in the literature in the context of multi-rotor helicopters.

Down the centreline of the aircraft, the wakes from the individual rotors interact very strongly, leading eventually to a strong upwelling of vorticity just behind the rear rotors of the aircraft. The unsteadiness and variability of the flow in this "rooster tail"-like structure, and the likely strength of the interaction with the under-fuselage and empennage of the aircraft as illustrated, would suggest the presence of some quite extreme buffeting of the airframe at this flight condition. One might speculate that suppressing the effects of this interaction on the dynamics of the vehicle might need a control system of quite high bandwidth - possibly even beyond that which actuation via the loads on the rotors can sensibly provide.

Visualisations of the flow such as those presented in Fig. 4 illustrate the power of numerical simulation in being able to generate key insights into the relevant physics - as well as in raising many additional questions which lead naturally to further exploration and discovery. Given the inherent complexity of the outwash field that numerical simulations reveal to be generated by aircraft such as this, the question then naturally arises as to how we might encapsulate results such as these into a representation that is practically useful to the eVTOL community - for instance to provide operators with an appreciation of the range of outwash velocities with which they are likely to have to contend, given the range of vehicles that they plan to operate from a given facility. Ideally, given the community's lack of direct experience with eVTOL aircraft to date, such a representation would, for instance, allow easy comparison with the properties of the more conventional rotorcraft with which they are already reasonably familiar.

5 BASIC THEORY

To this end, we can exploit some simple theory to expose the salient dependencies and their associated scaling factors. Newton's Second Law of Motion, applied to the fluid as it passes through the rotors, 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

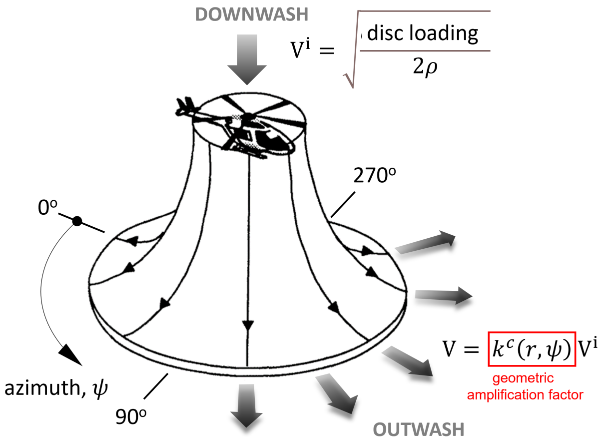

Figure 5
Relationship between the downwash velocity V^i and the outwash velocity V. (Image adapted from Ref. 1.)

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

This expression embodies the fundamental idea that the downwash velocity below the vehicle should scale according to the square root of its disc loading W/A, where W is the weight of the aircraft and A is the total area of all of its propulsors.

Equation 1 is, of course, approximate, and various objections to its direct use can be raised - especially in the present context. 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, or perhaps a favourable interaction between the ground and the airframe, is used to augment the thrust that is produced by the aircraft. Indeed, even in pure helicopter applications, this result is strictly only applicable if the vehicle is 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 Fig. 5) can be written as

$$V = k^c(r,\psi)\ V^i \tag{2}$$

The geometric amplification factor $k^c(r,\psi)$ 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 azimuth, ψ, and the distance away from the aircraft, r, at which the outwash is measured. Crucially, we assume that $k^c(r,\psi)$ itself is independent of the disc loading so that all dependence on this parameter is contained within V^i.

Given the number of parameters on which $k^c(r,\psi)$ is dependent, it should be readily apparent that the process of characterising the geometric amplification factor for any particular aircraft can turn very quickly into a laborious and time-consuming exercise, especially if the task is to be accomplished to any comprehensive degree. Practically, we are forced to resort to numerical simulations of the type that was presented in Section 4 to produce this data, or to wind-tunnel experiments or real-world measurements to produce spot-values for $k^c(r,\psi)$ at judiciously-selected points in the outwash field. The challenge, with all these approaches, is to produce truly representative data for the geometric amplification factor, and in so doing to characterise properly the salient properties of the outwash field. There are several potential pitfalls to be avoided, and this topic is returned to in detail in Section 7 of this paper.

Despite these caveats, the value of expressing the velocities in the outwash field in the form of Eq. 2 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 any other aircraft relative to that of the reference aircraft. From Eq. 2,

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

In this expression, 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.

Indeed, Eq. 2, and particularly Eq. 3, encapsulates the key physical insight that underpins our analysis - namely that the strength of the outwash field that is produced by any particular aircraft can be expressed as the product of two complementary effects: firstly, the direct influence of the disc loading of the vehicle's propulsors in scaling the magnitude of the velocities within the outwash field, and, secondly, the dependence of the shape of the outwash field, and potentially any local amplification of the velocities, on the details of the vehicle's configuration.

This conceptualisation allows us to compare the characteristics of existing eVTOL aircraft, and, indeed, to gauge the likely strengths of the velocities within their outwash fields relative to the velocities that are produced in the outwash fields of more conventional helicopters.

6 SCALING ANALYSIS

In this vein, Fig. 6 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 LHA-type naval vessels[12].

Despite the fact that, for obvious commercial reasons, eVTOL manufacturers tend to keep the true weight of their aircraft fairly close to their chests, Fig. 6 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. Higher disc loading leads inevitably to higher downwash velocities through the propulsors, as per Eq. 1.

Care is needed at this point. 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 with the surface below the aircraft to be significant. The theory that was presented in the previous section of this paper shows that this might not always be the case, as we explain next.

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 factors, all of which are contained within the geometric amplification factor, $k^c(r,\psi)$, defined in Eq. 2. The two most important confounding factors are, 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 (in other words, the aircraft's configuration as expressed in non-dimensional terms).

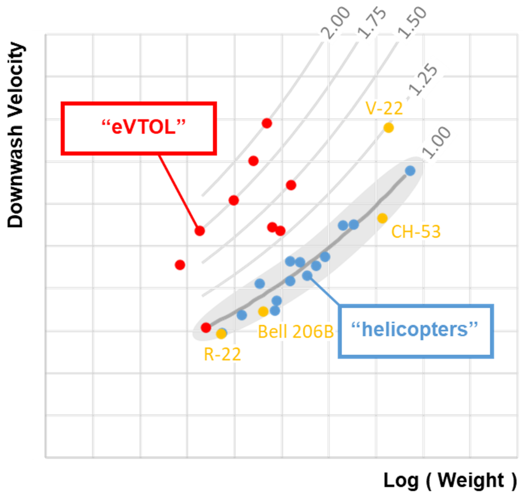

Figure 6
eVTOL aircraft generally create higher downwash velocities than helicopters that have the same weight. (Image adapted from Ref. 11.)

In terms of assessing the risk to ground personnel and infrastructure, for instance in the context of vertiport design, arguably the fairest results are obtained if the outwash is compared at the same distance from each aircraft. 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.

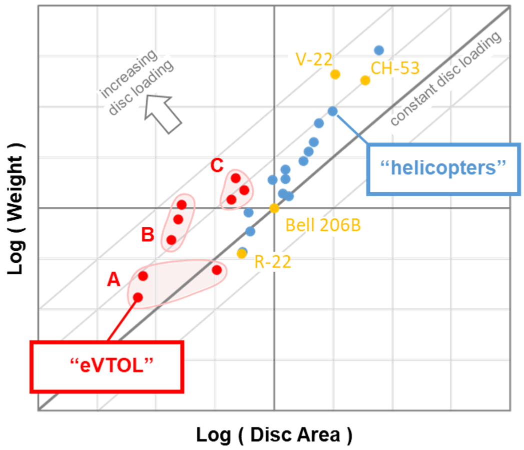

Figure 7
eVTOL aircraft divide into three clusters when their weight and size (as represented by their total disc area) is compared to that of conventional helicopters.

To lend further insight into this argument, the weight and total disc area of the same group of eVTOL aircraft as plotted in Fig. 6 are compared in Fig. 7. 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. This argument has also, arguably, allowed the eVTOL community to distance itself from the very obvious outwash-related issues that have been displayed, often in rather spectacular form (see, for instance, Ref. 13, and Ref. 6, Appendix I), by multi-rotor, highly disc-loaded, but heavy aircraft such as the V-22 Osprey.

What is a little more interesting about Fig. 7, 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.

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 weight. These aircraft should perhaps most prudently be treated with suspicion regarding the characteristics of their outwash, in the sense that specific features of their design might lead them, despite 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 of the work presented here - 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 Fig. 7, 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 produce velocities out across the ground which are surprisingly high - especially if our expectations are based on experience with more conventional helicopters.

7 PRACTICAL IMPLICATIONS

The question then remains as to how we combine relatively high-level analyses and predictions, such as those presented above, together with more detailed physical insights of the type presented in Section 4, to synthesize the rigorous understanding of the outwash phenomenon, as it relates to eVTOL aircraft, that will be required to manage the safety of operations of vehicles in this new class when they come into service. Hopefully the arguments presented above have given some indication as to how a combination of theoretical analysis and numerical simulation, supplemented, of course, by carefully-structured real-world measurement and laboratory-based experimentation, might be used in a mutually-reinforcing and supportive way to make meaningful progress.

7.1 Numerical Simulation

Especially for those aircraft that are now well advanced into their flight test programmes, first recourse might indeed be to numerical simulation in order to confirm that their outwash characteristics will be benign enough for them to be taken into service without significant modification. Such analysis should be seen as a definite precursor to, if not a substitute for, real-world tests.

Indeed, numerical simulation offers a relatively inexpensive and rapid route to being able to quantify the characteristics of the outwash of any aircraft, notional or real, as well as for exploring the likely real-world outcome of any configurational changes that might be adopted to ameliorate any outwash characteristics that are deemed to be unacceptable. Care needs to be taken however that we do not delude ourselves into an overly-sanguine characterisation of the properties of the outwash that is generated by any particular aircraft, simply through the use of numerical algorithms and packages that are not fit for purpose. It is very clear that the dynamics of the flow in the outwash field is dominated by the mutual interaction of the wakes that are created by the aircraft’s various propulsors. As described earlier, these wakes are essentially vortical in nature, and indeed the structures that are formed on the ground plane are strongly influenced by the various vortical instabilities to which the wakes of the rotors are inherently prone.

Many industrial CFD packages are inherently incapable of resolving the vorticity within the flow, and tend to diffuse and dissipate it long before it has had time to develop into the complex formations and patterns that characterise the flow within the outwash. The vorticity above the ground is often particularly ancient, especially when its age is measured in terms of the number of rotor revolutions that have elapsed since its creation on the blades of the propulsors.

This sets very high standards indeed in terms of the accuracy and stability of the numerical algorithms that must be used to model the flow, and mandates the use of methods that are able to conserve the vorticity and maintain its structure almost indefinitely. These observations extend not only to the traditional CFD methodologies, such as those based on the Reynolds-averaged formulation of the Navier-Stokes equations - which often provide a particularly confused view of what constitutes genuine vortical structure in the outwash and what constitutes turbulence - but also to the use of Lagrangian methods, such as the various vortex-particle methodologies that seem very attractive in terms of producing rapid, realistic-looking solutions but where errors in the location of the vortical structures within the flow tend to build up rather insidiously over time. The very serious risk is that, through the use of inappropriate simulation tools, the velocities within the outwash are mischaracterised, not only in terms of their spatial distribution, but also very likely in terms of their magnitude as well as their inherent variation over time.

Where properly used, however, numerical simulation can provide a range of insights that other approaches are simply unable to, both in terms of characterising the properties of the outwash field that is likely to be generated by any particular aircraft, real or imagined, and in terms of exposing the physics that is responsible for those properties. The greatest utility of numerical simulations is perhaps indeed in replicating the physics of inherently unphysical systems - in other words, in paring away those elements of the real-world system that are irrelevant and peripheral and exposing the underlying mechanisms in clear and unequivocal fashion. A simulation of two rotors, represented as a set of lifting elements devoid of hinges, hubs and supporting structures, hovering above a ground plane that is represented as perfectly smooth and infinite in extent, can often tell us more about the behaviour of the real system than measurements on the real system itself. The prospect of such numerical experiments is that they might lead to design insights that can be incorporated into the next generation of eVTOL aircraft, if not the current.

7.2 Measuring the Outwash Field

Indeed, what we measure, and how we interpret those measurements, is often very strongly influenced by our preconceptions of how the system should behave. The biggest problems arise where our preconceptions do not properly represent physical reality. The momentum-based view of the structure of the outwash field, that is commonly used within the helicopter community, is a particularly good example of this phenomenon. When characterising the properties of the outwash field using this approach, the velocity at any particular station in the flow surrounding the aircraft is typically represented in terms of a mean component, upon which a root-mean-square fluctuation can then be superimposed. Often the maximum velocity encountered at the station is provided alongside this basic description. This particular statistical representation of the velocity derives from a preconception of the flow as existing in the form of a turbulent jet, and this conceptualisation was originated early in the history of the study of rotor outwash on largely pragmatic terms - effectively by stretching the analogy between the flows that are generated by the propulsors of jet-lift aircraft, and the ostensibly more complex flows that are produced in the wakes of helicopter rotors. If one reads the relevant literature carefully, it becomes very clear that this particular characterisation of the flow was adopted by the originators of the approach with full appreciation of the limitations of their analysis - but also after taking the pragmatic view that a more appropriate characterisation would be very difficult to cast in practically useful form given the state of the art at the time.

Unfortunately, we are left with the legacy of this early work, and indeed its uncritical adoption and continued use is partially responsible for sustaining a number of mis-conceptions regarding the destructive power of rotorcraft downwash/outwash that tend to pervade the rotorcraft community. When the evolution of the outwash field is re-conceptualised in terms of the dynamics of the vorticity that it contains, then a much more granular view is obtained, in which the existence of these statistical constructs can be called into serious question. In a flow which consists of a set of discrete vortices propagating across the ground, for instance, it becomes very difficult to sustain the idea of an underlying mean flow, and indeed, any attempt to calculate such a value will seriously underestimate the global effect of the outwash in the presence of any features in the flow, such as individual vortex cores, that might cause the flow at any particular point to occasionally reverse direction. Use of a root-mean-square value to characterise the unsteadiness within the flow makes an underlying assumption as to the statistical distribution of fluctuations about the mean, and is biased significantly upwards by the largest, but also perhaps least frequent, perturbations to the flow. Measures such as the maximum velocity within the flow are statistically non-robust, since, at least in principle, larger values might always be observed if the system were to be monitored for just a little longer! Although there will always be a need to condense the huge amount of data that is required to fully characterise the outwash field into a more digestible form, we should be careful that we do not obscure the salient physics in the process.

7.3 Acknowledging the Human Factor

It is hard not to be left with the nagging feeling that these historical metrics do not properly encapsulate the vital statistics of the velocity distribution within the outwash field that are fundamental to a firmer grasp on the problem of ensuring the safety of VTOL aircraft more generally. The very real danger is that a flawed characterisation, especially if justified solely on the basis of historical precedent and without challenging the basic assumptions, might lead to a characterisation of the properties of the outwash field that is either fundamentally misleading, or that, perhaps even unbeknownst to us, speaks to a question other than that to which we would ideally like to have an answer.

Indeed, the flows in the outwash are inherently time-dependent and irregular, yet most of our data relating to the effect on humans that are immersed in the outwash field is expressed in terms of the overturning moments that are induced by constant winds. It is known that the ‘startle’ effect of being hit by a transient gust of wind can cause greater upset than being exposed to the same, constant wind velocity, and indeed that buffeting at certain frequencies can excite the human physiological response more easily than others[14][15]. The situation becomes even more complex when very human characteristics such as frailty or infirmity are taken into account - yet our existing armamentarium of techniques applies most readily to military personnel, and largely ignores the diversity of human condition that any public transport system should be designed to accommodate.

Given the advances in fluid mechanics, and, indeed, in statistical science within the last decades, particularly when characterising the behaviour of systems that are subject to discrete, and potentially rare, "black swan"-type upsets[16], we should perhaps consider as a community how we change our conceptualisation of the outwash field, and modify our approach to characterising the flows that our designs will create so that the information that we have to hand more pertinently and accurately represents the true likely effect that these vehicles will have on their surroundings. Developing this new basis will take time, but the end result will be overwhelmingly positive in terms of the confidence that can be placed in our analysis. In the mean time, those able to collect real-world measurements would do the community a great service if they collected and stored their raw data in a form that is amenable to re-processing in the light of new theoretical developments.

7.4 Quantifying the Outwash Field

Naturally, such fundamental questions and philosophical ponderings are all too easily dismissed as indulgent academic issues, despite the fact that they have profound real-world repercussions. Meanwhile, aircraft manufacturers are, of course, facing the very real pressures of bringing their products to market. Their concerns that late exposure of downwash-related problems with their aircraft will delay their entry into service are entirely understandable, yet it seems obvious that any problems should preferably be exposed in test rather than during actual operations where stakes are significantly raised. Given the very tight timelines in this respect, there is a need for a pragmatic way forward. The following guidance might be useful in the short term.

Firstly, preliminary data suggests that the velocities in the outwash below certain eVTOL aircraft may, in some instances, exceed those that are measured in the outwash of more conventional rotorcraft by quite a considerable factor. Two effects conspire to produce this outcome: the elevated disc loading of eVTOL aircraft relative to conventional helicopters with the same weight, and the fact that elements of the configuration of eVTOL aircraft tend to produce wake structures that are conducive to the generation of significantly higher outwash velocities than those found in the flow that is generated under similar operational conditions by more conventional rotorcraft. Realising this, operators and manufacturers should be prepared to take appropriate measures to compensate in terms of the operational procedures that they advocate and adopt for when their aircraft are flying close to the ground - particularly in the presence of personnel, passengers, and unsecured artifacts and infrastructure.

Secondly, the flow that is produced in the outwash of aircraft that have the compact, multi-rotor configuration that is characteristic of many eVTOL designs is likely in most cases to be far more complex than that which is produced by conventional helicopters. The interaction between the wakes of the various propulsors is particularly responsible for the formation of structures in the flow out across the ground beneath the vehicle that are not seen in the outwash of more conventional helicopters. A particularly notable feature of the outwash that is generated beneath a multi-rotor aircraft when operated close to the ground is the presence of the set of concentrated and highly turbulent jets of flow that invariably seem to form along the confluence of the wakes of its various propulsors. These jets tend to induce very high velocities along configuration-specific, but fairly narrowly-defined axes out along the ground plane, and, from a practical perspective, are likely to be the features within the outwash field of an eVTOL aircraft that are most likely to cause upset to personnel and infrastructure on the ground nearby.

In terms of experimental quantification of the outwash that is generated by any particular eVTOL design, the existence of these compact flow features implies the need for a matrix of test sensors that is spatially far more dense than is currently used for similar measurements of the outwash that is produced by conventional helicopters. Too sparse a matrix will simply allow the more compact and directional structures within the flow to slip between the fingers of the measurement process, with obvious implications for the accuracy of any quantification of the velocities in the outwash field[17]. Again, here lies a distinct opportunity for self-inflicted harm: overly sanguine predictions of the velocities in the outwash will be the inevitable outcome of an incomplete or cursory measurement campaign.

Thirdly, the inherent unsteadiness of the flow in the outwash should be acknowledged in any test procedure. Our simulations suggest that the ground-jets mentioned above have a propensity to meander and change their orientation over time, even if the aircraft meanwhile remains fixed in its attitude and orientation. Individual measurements of the velocity in the flow near these jets will thus not necessarily register their presence. Similarly, time-averaging the data runs the risk of smearing these features out between the readings on several sensors and potentially misrepresenting their true strength. In this vein, the sensors in any measurement array should have sufficient bandwidth to capture the full frequency content of the velocity signal, and measurements should ideally be time-stamped to allow the existence of transient features in the flow to be properly identified by cross-correlation between the measurements at various sensors.

7.5 Effect of Operating Condition

It is clear too that the characteristics of the outwash field that is produced by any particular eVTOL aircraft will be very sensitive to the height of the aircraft above the ground, the presence of any winds, and, indeed, to the dynamic state of the vehicle itself. It cannot be assumed that the strength of the outwash field varies monotonically with any of these variables - so, for instance, that the outwash velocities will be highest with the aircraft closest to the ground. Indeed, a particular characteristic of multi-propulsor aircraft, and especially those that have rotors the size of many current eVTOL aircraft designs, appears to be the ability of their outwash to transition from one distinct flow state to another, most notably as the height of the aircraft above the ground is varied. A deep, turbulent outwash field, produced by the rotors of the aircraft when hovering at altitude, can give way very swiftly to a thin, fast-moving surface layer, for instance, as the vehicle descends to land, and the effects of these different types of flows on bystanders and nearby infrastructure is likely to be very different. This inherent complexity of the relationship between the operating conditions of the aircraft and the structure of its outwash needs to be acknowledged when setting up any test matrix that is designed to expose the operating conditions at which the velocities in the outwash field might be at their greatest.

7.6 Vertiport Design

The inherent complexity of the outwash problem will need also to be taken to heart by the vertiport community, particularly in terms of the design of landing and take-off zones and in the definition of the operational procedures that should be followed when these aircraft are operated close to the ground. More simplistic representations of the effects of the outwash, for instance through the definition of a radially-symmetric region of exclusion around the aircraft[3][4], are certainly inconsistent with the azimuthal inhomogeneity in the outwash field that numerical simulations suggest will be generated by some of these new vehicles.

Secondly, any approach that uses disc loading (or, worse still, aircraft weight) in isolation to determine the size of the exclusion zone that is required around any particular aircraft runs the risk of neglecting the fundamental role of the vehicle's configuration in determining the magnitude of the velocities that are produced within its outwash field. Our preliminary data suggests that, if care is not taken to account properly for the additional effect of aircraft configuration, then, in certain cases, the danger posed by the vehicle's outwash to personnel and infrastructure on the ground nearby might be significantly greater than expected.

Finally, the situation is further complicated if a range of eVTOL aircraft with different sizes, weights and configurations is expected to operate from the same facility. Both the shape and the strength of the outwash field that is created below a multi-rotor aircraft when operated close to the ground are likely to be particulary sensitive to the details of the aircraft's configuration, (so for instance, to the number and location of the rotors on the airframe, to their height above the ground and so on). What this may mean practically is that each individual aircraft type that is intended to operate from any particular facility may need to be assessed on its own merits regarding the effect that its outwash is likely to have on its surroundings.

7.7 Ground Operations

Again, the extent of the azimuthal asymmetry of the outwash field that might be produced by some eVTOL configurations will come as a distinct surprise to those whose experience is founded on conventional helicopter practice. The outwash from an eVTOL aircraft is likely to contain hidden within it at least as many concentrated jets of flow as there are rotors on the aircraft, and, to all intents and purposes, the orientation of these jets will remain fixed relative to the *aircraft* axes, rather than relative to axes fixed to the ground, as it manoeuvres on the airfield. A surprise encounter with one of these features, perhaps formed in the outwash from an aircraft that is manoeuvring or positioning itself on the ground, could be singularly upsetting to an unsuspecting participant standing nearby - the closest analogy perhaps being to an encounter with the sidewash from the tail rotor of a conventional helicopter. Although the effects of high outwash velocities will very quickly become apparent in day-to-day operations, prudent vertiport designers might well make provision for the monitoring of peak values at critical locations around their facility, not only during the commissioning of any new vertiport, but also during subsequent day-to-day operations.

8 CONCLUSIONS

The hope is thus that the work presented here will help to motivate the rotorcraft community to develop the broad understanding of the downwash/outwash-related characteristics of eVTOL aircraft that designers, operators and regulators will need to have to hand when ensuring the safety and utility of these vehicles as they become an ever more common feature of the urban transport infrastructure. Indeed, it is hoped that the discussion presented here will encourage and stimulate a conversation between theorists, modellers, operators, manufacturers and regulators in the realisation that all have a role to play in raising our understanding of the outwash phenomenon to a level where we, and the public that will rely on our diligence in this respect when they travel in these machines, can be assured that the technology is as safe as it possibly can be.

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