UNDERSTANDING THE AERODYNAMICS OF eVTOL OUTWASH

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ABSTRACT

The flows out across the surface that are produced by eVTOL aircraft when operating close to the ground are very different in character to those produced by the conventional helicopters on which much of our current understanding of rotorcraft outwash is based, yet accurate quantification of the velocities within these flows is seen as an important part of ensuring the safety of this new form of aerial transport. An analysis of the fundamental fluid mechanics that governs the formation of the flows in the outwash below these aircraft shows the importance of the inherent instability of the vortical structure of the wakes produced by their propulsors in governing both the form and strength of the flow out across the ground below the aircraft. Numerical experiments show the outwash to be particularly susceptible, through the long-term action of this vortical instability, to losing the symmetries that might have been imparted to it by the geometry of the aircraft. This results in flows that in many cases are far more spatially inhomogeneous than might be expected, where the overall characteristics of the flow can vary considerably over time, and, indeed, where the character of the flow might be dependent on the way in which it was formed in the first place. These observations suggest that we might need to know a great deal more about the physics that governs the aerodynamic behaviour of these systems before we place too much faith in our ability to quantify the risks posed by these aircraft to bystanders and infrastructure that might become exposed to their outwash.

1. INTRODUCTION

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 is 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 our current conceptualization of the strength and form of the outwash that might be produced out across the ground plane by a rotorcraft when operated close to the ground is based on long experience with conventional helicopters[1] (see Fig. 1).

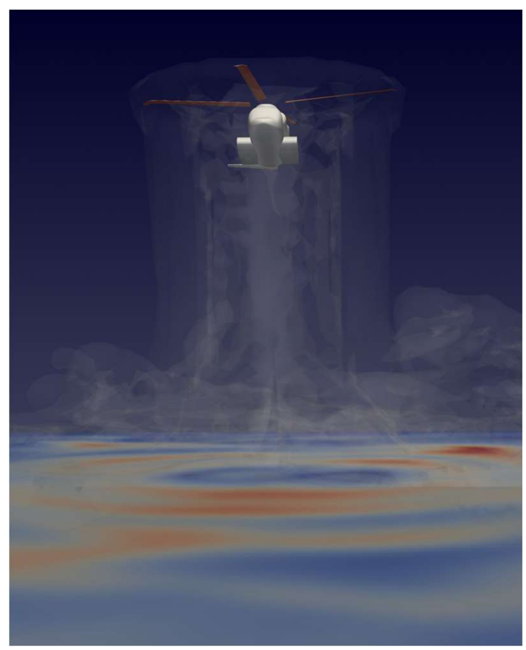

Fig. 1. Numerical representation of the downwash that is produced by a large conventional helicopter when in a high hover, showing how, following its contact with the surface below the aircraft, the flow is deflected outwards across the ground to form the outwash.

Recent events, *e.g.,* those described in Ref. 2, suggest that our understanding of the properties of helicopter outwash might be incomplete, and potentially founded on an overly-simplistic representation of the physics of the flow. eVTOL aircraft have particular characteristics, however, that recent numerical studies[3,4] have suggested might make the structure of the flow in their outwash even

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more complex, and indeed both quantitatively and qualitatively very different to that produced by more conventional helicopters. Although the vehicles are generally quite compact, their use of electric propulsion invariably leads to a configuration with multiple rotors, and, by helicopter standards, these rotors are relatively small and highly loaded.

Simple scaling arguments indicate that the velocities in the outwash that they will produce will thus be proportionately higher than those produced by a helicopter with similar weight. The aerodynamic interference that arises in the juxtaposition of their rotors may cause the pattern of outwash produced on the ground by eVTOL aircraft to be particularly complex (see Fig. 2). Indeed, numerical experiments show the outwash pattern to be strongly dependent not only on the relative placement of the rotors but also on the conditions under which the aircraft happens to be operating. This paper extends and amplifies previous work in this regard by focusing on the various physical mechanisms that are at work within the outwash flows that are produced by both helicopters and multi-rotor eVTOL aircraft, and that are responsible for this inherent complexity.

2. REGULATORY IMPACT

The regulators appear to be open to the prospect that the outwash properties of eVTOL aircraft might be sufficiently different from those of the types of VTOL aircraft that have historically operated from our heliports and other ground infrastructure that additional insight into the particular characteristics of this class of vehicles might be warranted. Indeed, although limited information is available from the real world[5,6], what little information has been released into the public domain generally supports the major findings of earlier numerical analysis[3]. Although the quality of the data currently in the public domain is open to criticism on several grounds, measurements seem to confirm, for instance, the basic proposition that the outwash generated by these vehicles can be extremely inhomogeneous – to the point that, at least along certain axes, the outwash might become focused into intense, jet-like structures (see Fig. 2). These observations lend credence to the physical mechanisms postulated in works such as Ref. 3, and hold out the prospect that a fundamental physical understanding of how the outwash field originates within the interactions of the wakes of the individual rotors of the aircraft might eventually lead to methods for its control, and potentially also for its amelioration[7].

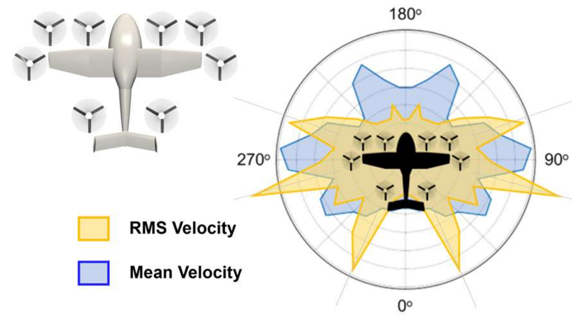


Fig. 2. Predicted variation of velocity with azimuth in the outwash below a representative eight-rotor eVTOL aircraft. Note the extreme inhomogeneity in the velocity field and the existence of axes along which the flow is significantly stronger or more unsteady than elsewhere.

In the light of the information that is emerging, the regulators seem to be moving in the direction of acknowledging the importance of characterizing the velocities that are generated in the outwash when assessing the compatibility of these aircraft with particular landing sites – particularly in terms of the risk that their outwash might pose to facilities and infrastructure, and especially to bystanders that might find themselves near to an operating aircraft. EASA MOC-2 SC-VTOL, for instance, contains the requirement[8] that “the downwash of the aircraft should be characterised and reported to allow safe operation and minimisation of hazards to ground personnel,” and the latest update of FAA EB-105 advocates identification of those areas surrounding the aircraft where the outwash velocity exceeds a defined velocity threshold[9]. The intent is that these measurements be fed into the establishment of ‘caution areas’ surrounding the aircraft, or lead to constraints on the minimum dimensions of the surfaces from which these vehicles are allowed to operate.

These documents contain little detail or substance however with regards to what measurements should be taken or how they should be processed in order to yield a robust assessment of the risk posed to bystanders and nearby infrastructure. Indeed, the community has already been given its first salutary lesson in how such information, gleaned in the absence of a full understanding of the flow physics, might be mis-interpreted to the detriment of the industry. In a rather unfortunate episode[6], essentially raw measurements were released to the public, accompanied by very little of the interpretation that would usually be expected when

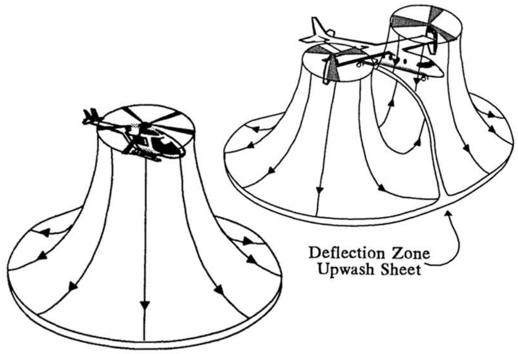


Fig. 3. The pervasive representation of the outwash field below single-rotor helicopters (left) as well as vehicles with multiple rotors (right) is as a structured, highly symmetrical flow out across the ground. (Images from Ref. 1.)

dealing with such a complex topic. The resulting lacuna was filled very quickly by the trade media[10,11], who were handed a golden opportunity to overplay the dangers implicit within the outwash generated by eVTOLs. It is not hard to imagine, albeit perhaps with the benefit of hindsight, that a very different outcome could have resulted from a more careful presentation and contextualization of the data in terms of the underlying physics.

The urgency from all sides to put protective measures in place as soon as possible is understandable, especially given commercial pressures on, and from, the manufacturers of these aircraft and the developers of the infrastructure from which they will operate. Given the nascent state of our understanding of even the general characteristics of the outwash that is produced by this new class of aircraft, there is a distinct danger, however, that the cart will be placed before the horse, and that provisions might be put in place that later turn out to be ill-founded or inappropriate.

3. UNDERSTANDING eVTOL OUTWASH

This paper thus will attempt to set out some of the key elements of our present understanding of how the particular features found in the outwash of both single- and multi-rotor vehicles come into existence, and how these depend both on the geometry and configuration of the aircraft as well as potentially on its operating condition. In the absence of real-world information, we will rely heavily on insights obtained from numerical simulations. Yet, in that vein, the power of computation to reveal details of the physics that are inaccessible to anything but the most intricate and expensive of experimental techniques will hopefully become apparent. The quality of insight turns out to be critically dependent on the quality of the numerical tools that are used to investigate the flow, however. We have written extensively elsewhere on this topic[3,7], and, in the present work, such concerns will largely remain implicit in our discussion of the details of the mathematical structures (and strictures) that underpin the salient physics.

Our particular aim will be to dispel several counterproductive fictions that have arisen within the community over the years regarding the character of the outwash field, and that at present seriously hamper definition of the appropriate measurement strategy for its quantification. For instance, conceptualization of the outwash velocity at any point within the flow as a mean velocity 'stream' (see Fig. 3) onto which perturbations might then be superposed to represent the inherent unsteadiness of the flow, turns out to encapsulate very poorly the discrete and irregular nature of the flow as well as the distances out from the aircraft to which the velocities in the outwash might be appreciable. Yet, when the prevalent conceptualization of the flow out across the ground as inherently jet-like is replaced with a model that properly accounts for the structure in terms of the wake-like flow that is produced by the individual rotors, and where the considerations of momentum interchange that are promulgated by simplistic numerical modelling are supplanted by a view in terms of the (invariably unstable) interaction between the vortical structures that are produced in

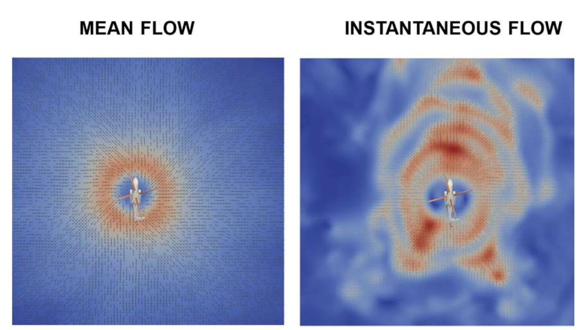


Fig. 4. Numerical simulation of the flow velocities in the outwash below a hovering helicopter (Red denotes the highest velocities, blue the lowest). Although the velocities in the outwash appear smooth and regular when averaged over significant lengths of time, the instantaneous velocities in the outwash are significantly higher and less uniform. (Images from Ref. 4.)

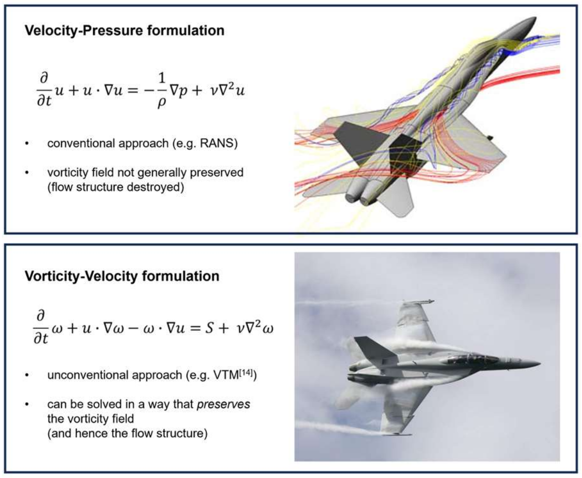


Fig. 5. The equations representing the physics of the fluid can be formulated in different, but equivalent, ways. The velocity-pressure formulation is commonly used as the basis of numerical analyses of the flow, but methods based on a formulation in terms of vorticity and velocity tend to preserve more efficiently the underlying structure of the flow as it evolves, and are thus better suited to modelling the phenomena discussed in this paper.

these wakes, the insights so obtained are highly instructive[4] (see Fig. 4).

A range of numerical explorations conducted over the last couple of years, sponsored largely by the UK Civil Aviation Authority, has raised the possibility that the character of the flow in the outwash might be even more complex than previously imagined by the engineering community[4]. Interestingly, this is despite the fact that much anecdotal evidence exists to suggest that some users and operators have long been aware of the particular hazards posed by some of the more granular, unsteady and concentrated features of the flow out across the ground that their rotorcraft are capable of producing, and even indeed that, in some instances, heuristics exist to ameliorate some of the most pernicious effects of the outwash on the environment in which the aircraft is being operated[4].

As the science struggles to keep up with the practice, and in the spirit of Igor Sikorsky's famous quote regarding the lag between the practical exploitation of this particular class of machines and our understanding of the reasons for their behaviour, this paper is based on the premise that we need to understand a lot better the likely characteristics of the system that we might be measuring before indeed we set out to quantify the properties of the flow that are most salient to the safety issue.

In stark contrast to the representations of the outwash shown in Fig. 3, numerical experiments, supported by the limited experimental data available so far, suggest that the flow in the outwash below a rotorcraft is geometrically complex, time-dependent, potentially very difficult to characterise in any way that is robust to the vagaries of the experimental setup, and definitely varied enough in shape and form to warrant detailed and careful study. These qualities will all need to be taken into account in constructing any experimental programme that aims to characterize the strength of the outwash, lest we be seriously misled by the data so collected. This paper thus takes a side-step away from the quantification of the strength of the outwash that has largely been our concern so far[3,7], and instead aims to develop a more qualitative understanding of the likely character of the flow under various circumstances, as informed by an analysis of the constraints on, and opportunities for, evolution of the flow that arise from the underlying fluid dynamics.

4. MODELLING THE FLOW

In our view, the greatest insight into the physics of the flow is achieved by expressing the underlying equations of fluid motion in terms of the vorticity in the flow. The prime insight comes from realizing that the vorticity and the velocity are essentially two sides of the same coin, in the sense that the expression $\omega = \nabla \times u$ that defines the vorticity ω in terms of the velocity u essentially implies a means of conversion between any representation of the flow in terms of its velocity and its equivalent representation in terms of vorticity. This duality is illustrated in Fig. 5 – In this vein it might be useful to imagine the vorticity as constituting the 'skeleton' of the flow, the various constraints on the configuration of this field, as described in detail below, governing the kinematics and form of the flow in much the same way as do bones and joints – in this case, onto which the 'meat' of the flow, as represented by the velocity field, is attached.

The Navier-Stokes equation that defines the evolution of the vorticity within a flow that can safely be assumed to be incompressible (*i.e.*, one in which $\nabla \cdot u = 0$) can be written as

$$\frac{\partial \omega}{\partial t} + u \cdot \nabla \omega - \omega \cdot \nabla u = \nu \nabla^2 \omega + S \tag{1}$$

where $u \cdot \nabla\omega$ is the so-called advection term (see Fig. 6) which simply moves vorticity from one place to another in the flow, while $\omega \cdot \nabla u$ is the stretching term, which acts over time to align the vorticity with the direction of greatest strain in the flow, as embodied in the velocity gradient ∇u. The term $\nu\nabla^2\omega$, proportional to the fluid kinematic viscosity ν, accounts for viscous diffusion. A key insight that remains somewhat hidden in the standard 'velocity-pressure-density' form of the Navier-Stokes equations (see Fig. 5) is that the effect of viscosity is not to act as a dissipative mechanism within the flow but merely to spread the vorticity out over an ever greater volume as time progresses (since the term is conservative in the sense that that the integral of the vorticity over the domain remains constant under its action). Thus, in seeking dissipative mechanisms within the flow, we need to look elsewhere (see later). Finally, vorticity is introduced into the flow via the source term S, which, if we confine ourselves to the incompressible situation, can only be non-zero on solid surfaces that are immersed within the flow.

It is tempting to abuse the duality between vorticity and velocity by considering the vorticity distribution in some way to 'induce' the velocity distribution within the flow. Indeed, the ubiquity of this practice is evident in terms such as the "induced drag" of blades and wings. This conception comes from the fact that the definition of the vorticity in terms of the velocity, $\omega = \nabla \times u$, can be inverted via a vector identity (again assuming incompressibility) to give a Poisson equation

$$\nabla^2 u = -\nabla \times \omega \tag{2}$$

which can be solved for the velocity (up to the addition of a field, given by the gradient of a scalar potential, that arises when the boundary conditions are not simple – see below) once the vorticity distribution within the flow is known. This equation is essentially a differential form of the well-known Biot-Savart relationship, which, to our electrical engineering colleagues, *does* provide a means of determining, for instance, the magnetic field that is induced by a current flowing through an electrical conductor.

The problem with Eq. (2), if naively regarded, is that it allows for an interpretation of Eq. (1) in which the essential duality between the vorticity and the velocity is relaxed, even to the point of being lost, and instead where the vorticity is considered merely as an arbitrary vector field, unconstrained in any way

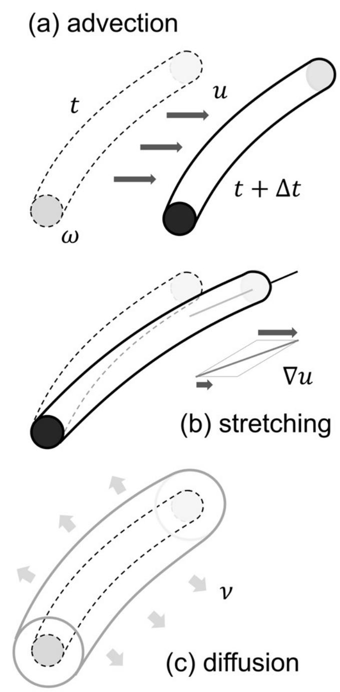


Fig. 6. Three different mechanisms for evolving the vorticity distribution in the flow are embodied in the vorticity transport equation (Eq. (1)). The deformation of a bundle of integral curves of the vorticity field under the action of these mechanisms is shown schematically.

by its relationship to the velocity field – other than of course through its evolution being governed by Eq. (1). Inverting the argument, the velocity can be interpreted similarly as an arbitrary three-dimensional vector field, unconstrained by its relationship to the vector field represented by ω in Eq. (1) – other than through representing perhaps an (approximate) solution to Eq. (2).

The idea of the vorticity field inducing the velocity field is however a fiction with considerable didactic and practical value and we will, on occasion, exploit it where it provides clarity or insight in the analysis that follows. In doing so, however, we will always be careful to preserve the insights into the evolution of the fluid that is provided by the mathematical foundation that is given above. Indeed, the idea of induction of the velocity field by the vorticity forms the implicit basis of several well-known numerical techniques, particularly those based on a representation of the vorticity field in terms of a discrete cellular distribution, particles or filaments, and representing the relationship between the velocity and the vorticity in some approximate way, for instance through a numerical solution of Eq. (2).

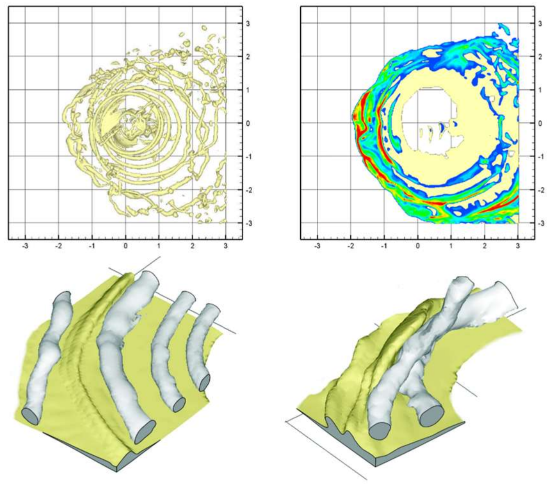


Fig. 7 showing the vorticity arising from viscous interaction of the rotor wake with the ground (by analogy with similar physics for a passively-advected scalar – see Ref. 12). Top left: vorticity distribution for a rotor moving slowly from right to left above the ground. Top right: associated source of vorticity from the ground. Bottom: two snapshots showing the local enhancement of the source that can result from interaction with concentrated elements of the rotor wake.

Importantly, though, the ability of these various numerical techniques to represent accurately the properties of the flow in the outwash is highly dependent on the extent to which the duality between vorticity and velocity can be maintained (or restored) in the numerical algorithm. To this end, a sequence of constraints on the vorticity distribution needs to be enforced in conjunction with the numerical advancement of Eq. (1) through time. In practical terms, the two most important constraints arise firstly in the somewhat self-evident expression $(\nabla \times u) \times \omega = 0$, which has important consequences for how the vorticity field can deform in the presence of gradients in the flow, and, secondly, in the fact that the vector identity $\nabla \cdot (\nabla \times v) = 0$ holds for any vector field v, which implies that the vorticity field should itself be divergence free.

This second relationship embodies a topological constraint on the evolution of the vorticity that takes on critical importance in understanding the evolution of the flow. Essentially, this constraint imposes the condition that the topology of the integral curves of the vorticity field (the set of vortex filaments, in a somewhat more relaxed parlance) remains invariant as the system evolves, and hence that these curves should either terminate on a boundary of the flow or form closed loops (an inference embodied in Helmholtz's well-known theorem). In other words, loops of vorticity that at one time are not interconnected cannot become so at any later time, or, equivalently, that any tangles that develop within the integral curves can be unravelled back to their configuration at an earlier time without disconnecting any one of the curves in the process.

The actual fluid dynamic problem to be solved is of course instantiated by defining suitable boundary conditions on the flow. Imposition of suitable boundary conditions on the solid surfaces of the rotorcraft itself results in a source of vorticity into the flow which eventually manifests as the downwash below the vehicle.

Indeed, the vortical mechanisms that contribute to the structure specifically of the *downwash* below the rotorcraft will be the topic of the next section of this paper. In contrast, the boundary condition that needs to be imposed on the flow near the ground (or on the surfaces of any buildings and other infrastructure below the vehicle) is of particular interest in understanding the physics of the *outwash*, and is usefully separated into a condition that the velocity have zero component normal to the solid surface (the so-called zero-penetration condition), and a second condition that, at the solid boundary, the component of the velocity tangential to the surface also be zero (the so-called zero-slip condition).

When the solid boundary below the system has relatively simple geometry (for instance if the boundary is flat, or consists of several orthogonal or parallel surfaces), the zero-penetration condition can be enforced by reflecting the vorticity distribution in the boundary and viewing the velocity field in terms of its equivalence to this composite vorticity field. In more complex situations, an additional, irrotational contribution to the velocity field arises (the gradient of the scalar potential mentioned above) when imposing this condition that cancels any component of the velocity normal to the boundary.

In terms of the zero-slip condition, there is considerable didactic advantage in assuming the flow to be inviscid ($\nu \to 0$) and thus in forgoing this boundary condition entirely. This approach has the distinct advantage of removing any fundamental dependence of the aerodynamics on the actual dimensions of the system – and thus in preserving a considerable degree of generality in the analysis. Indeed, many of the insights presented in the following sections of the paper have been generated after adopting this particular simplification.

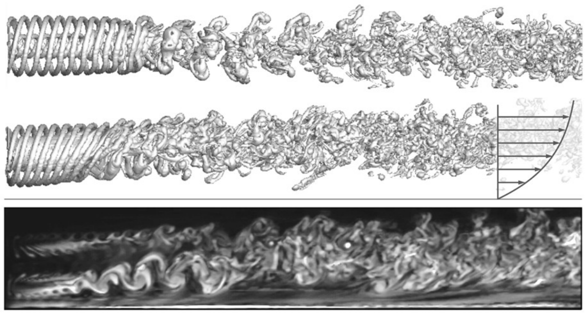


Fig. 8. The presence of an atmospheric boundary layer (ABL) can have a strong effect on rotor wake development. The images here extracted from numerical simulations of the relatively simple case of a rotor operating in the windmill brake state (Ref. 13). Top: rotor wake in uniform flow. Middle: rotor wake when an ABL is present, showing overturning and transverse convection. Bottom: heat map showing the distribution of vorticity extracted from the ABL through its interaction with the rotor wake.

In a more complete analysis, part of the source S of vorticity into the flow arises in the zero-slip condition through the creation of a layer of vorticity in the flow just above the solid surface. The spatial distribution of the vorticity in this layer as it forms is governed strongly by the structure of the flow just above the solid surface (see Fig. 7) and, if its strength is significant compared to that of the vorticity originating from the rotors, the interaction between the two fields as time progresses can have profound effect on the overall structure of the flow. The strength of the vorticity within this layer, and hence its effect on the subsequent dynamics of the flow, is proportional to the Reynolds number of the system. Given the various possibilities for how the length-scales that define the Reynolds number might be expressed, this statement can be interpreted in one of two different ways – firstly, in inferring that the flows created by smaller systems (drones, and model-scale rotors, for instance) will be more sensitive to the presence of this source of vorticity than larger rotorcraft, and, secondly, in inferring that the effects of this source will become more pronounced the greater the distance out across the ground away from the rotorcraft.

The zero-slip condition becomes particularly relevant in the presence of wind, especially if a boundary layer has had the time and space to develop to appreciable thickness in the air above the ground. The variation of velocity with height above the ground within this atmospheric boundary layer (ABL) implies the existence of an associated vorticity distribution, and the evolution of the combined vorticity distribution within the flow can be understood by examining the contributions to its dynamics from the various terms in Eq. (1). Indeed, two appreciable effects of the interaction between the rotor wake and the ABL are usually observed, as shown in Fig. 8. Firstly, stretching and convection in the boundary layer both lead to the progressive re-orientation of the vorticity in the rotor wake as it is swept downstream by the wind. When compared to the trajectory that the wake would follow in the absence of the boundary layer, this effect can alter the direction of propagation of the wake quite appreciably. Secondly, as illustrated in the bottom part of Fig. 8, both the convective and stretching terms in Eq. (1) are responsible for extracting vorticity from the boundary layer, and transforming it into an additional component of the vorticity distribution in the flow that influences the trajectory of the rotor wake as it propagates across the ground.

5. THE FLOW IN THE DOWNWASH

In the process of creating lift, each blade of each 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, of course, 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.

A snapshot of the vorticity distribution within the wake below a hovering rotor, obtained from a numerical simulation using the Vorticity Transport Model (VTM – see Ref. 14), which is a numerical technique that can be used to calculate the evolution of the rotor wake over time as a solution to Eq. (1) while maintaining very tight control over the topological constraints on the system described earlier, is shown in Fig. 9. The helical structure of the tip vortices is clearly visible, especially in the wake just below the rotor. It is clear though from this figure that the progression of these vortex sheets into the flow below the rotor does not continue for any appreciable distance before their geometry begins to take on a much more complex form.

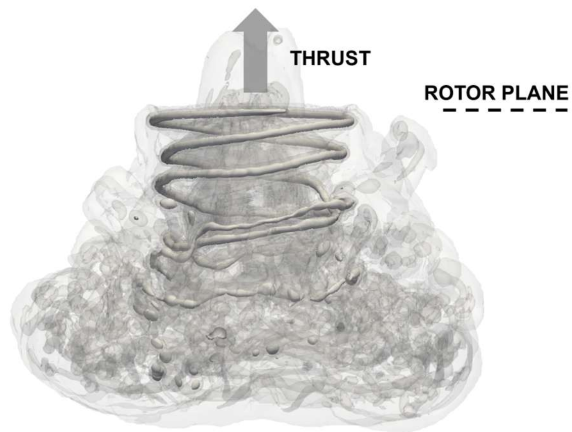


Fig. 9. Numerical simulation of the wake that is produced by a hovering rotor in free air, as visualized by plotting a surface on which the vorticity has constant magnitude. The underlying helicoidal symmetry of the system is inherently unstable, with the result that the structure of the wake succumbs very rapidly to disturbances that originate in small, local perturbations to the flow, but that grow quickly to finite size.

Indeed, the dynamics of these helical structures is inherently unstable. 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 intertwined. The most important forms of instability[15,16] 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 Fig. 9 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 Fig. 9.

The importance of this instability is that it causes the wake below the propulsor to transition through what can be thought of as 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 Fig. 10. 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 Fig. 9. 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 Fig. 9 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. This production of structure on ever finer scales, and the associated randomizing of the directionality of the vorticity field within any finite volume of the fluid (implying that the velocity also becomes ever closer to zero) is, indeed, we believe, the prime source of dissipation in the rotor wake.

The linear, early stages of the development of the flow in response to these instabilities is amenable to analysis. It can be shown, for instance by modelling the wake system as a set of inter-digitated, infinitely-long helical vortices[17], that the rate of growth of the perturbations to the wake structure associated with

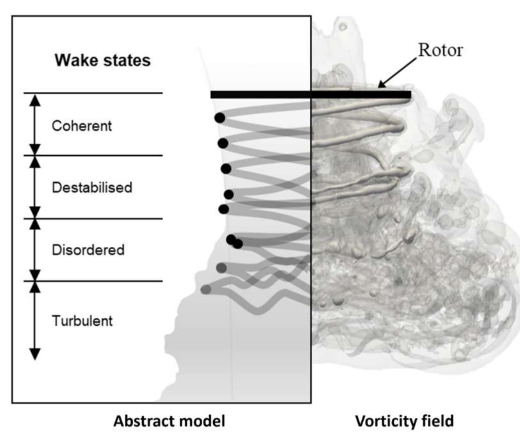


Fig. 10. Conceptual model showing the evolution of the structure within the rotor wake through a series of states as distance away from the propulsor is increased. This evolution has important consequences for the structure of the outwash field. (Image from Ref. 3.)

its inherent instability is influenced by the design of the rotor, principally by the number of blades and by how much the blades are twisted.

The non-linear regime, in which these disturbances have reached appreciable magnitude, is less amenable to direct analysis, but some important qualitative properties can be inferred from the mathematical analysis of the fluid dynamics that was presented earlier. Indeed, in these later stages of evolution of the wake, and as can be seen in the VTM calculation shown in Fig. 9, Helmholtz's theorem poses a particularly strong topological constraint on the evolution of the vorticity field – successive loops of vorticity within the wake cannot pass through each other and instead tangle around each other as the perturbations to the helicoidal geometry of the vortices reach appreciable magnitude. The associated re-orientation of the vortex filaments transverse to their original orientation that must take place as this tangling progresses, and the associated 'pinching' of the vortices (*i.e.*, the tightening of the radius of curvature of the vortices) promotes the growth of the short wavelength instability.

This dynamic, where the helical symmetry of the system (*i.e.*, invariance to a rotation coupled to advance at a prescribed pitch) is lost through the action of the inherent instability of the system, causing a configuration with a high degree of symmetry to be transformed into a state with fewer geometric invariances, is the first example of *symmetry-breaking* that we will describe in this paper. Further examples alluded to later in this work will show how critical this phenomenon is to understanding the dynamics of the flow not only in the rotor wake, but also in the outwash more generally.

It is also important to realise that the instability of the rotor wake is convective in nature, in the sense that at the same time as being swept downstream from their origins, the perturbations to the wake structure that are associated with the instability are also able to spread both upstream and downstream along the wake itself. A very successful model[18] for the dynamics of the wake in the presence of this convective element to its evolution was developed while trying to understand the role of these very same instabilities in the precipitation of the helical wake into the destabilized toroidal form associated with the onset of the Vortex Ring State (VRS). Indeed, for theoretical predictions to be consistent with experimental observations suggesting that a universal boundary for the onset of the VRS should exist (in the sense of being capable of definition solely in terms of non-dimensional parameters of the system), it follows that the maximum rate of propagation of disturbances along the wake has to be proportional to the (square root of the) thrust coefficient at which the rotor is operating. Given that the rate of convection of the vorticity into the flow below the rotor is similarly proportional to this parameter, it follows quite straightforwardly that, under all steady operating conditions (at least those where the rate of convection exceeds the rate of propagation of the disturbances, so potentially except when the rotor is in VRS), the effects of convection and spreading must equilibrate, for a given rotor design, to yield a similarly universal geometry for the wake in the presence of its inherent instability. This argument applies even when the wake has developed far enough for significant nonlinearity to be manifest in its dynamics, and thus is a useful extension to the predictions of linear stability theory.

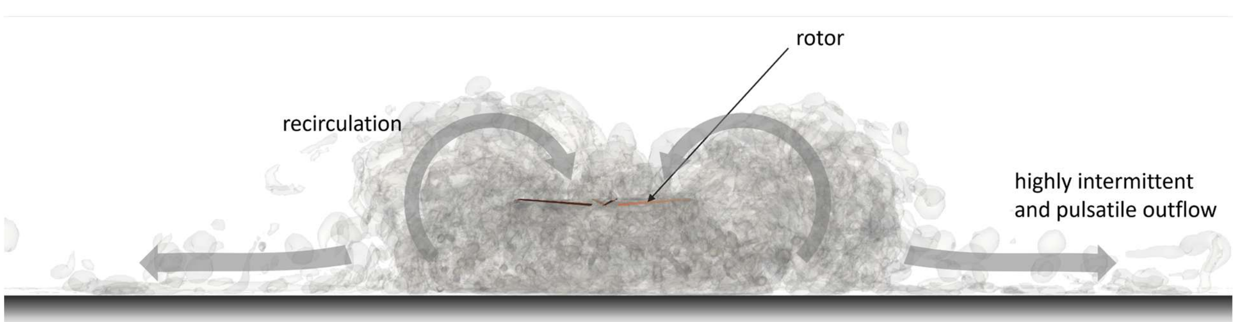


Fig. 11. Numerical simulation of the flow in the 'ground-induced Vortex Ring State', where convection into the flow below the rotor is not quick enough to prevent perturbations to the wake structure from propagating back to the rotor. The wake collapses into a toroidal, recirculatory form that is very similar to that observed when the wake enters the Vortex Ring State with the rotor in free air.

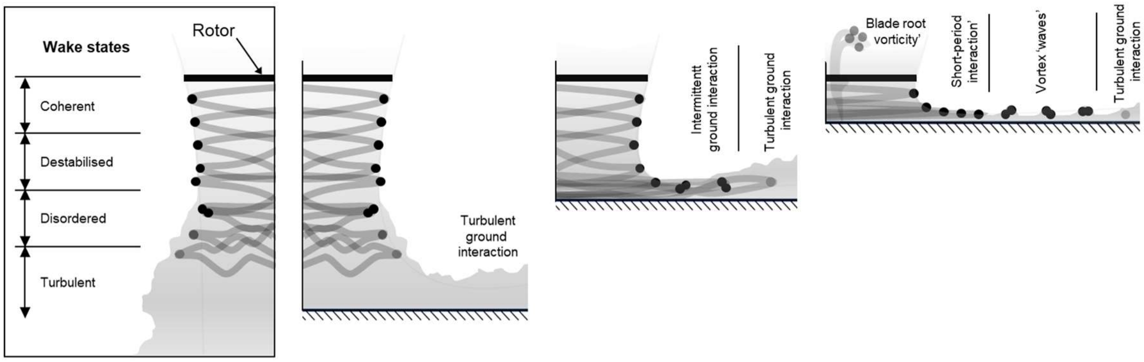


Fig. 12. Schematic explaining how the changes in structure of the outwash with the rotor at various heights above the ground can be related back to the effects of the natural instability of the wake and to the condition of the downwash at the point that it first makes contact with the ground (see Fig. 10). (Images from Ref. 3.)

Perhaps the most important extrapolation from this analysis (at least for the inviscid problem) is that the distance below the rotor to which the downwash should extend with appreciable strength (all else being equal) should scale simply and directly with the rotor diameter. In other words, larger rotors should produce a proportionally longer coherent element to their wake, extending down into the flow below the system, than smaller rotors. This dependence of the extent of the downwash on the *rotor* size and not on the *aircraft* size is generally not very well appreciated by the community, but has important practical consequences – for example for the relative effect on surrounding infrastructure of the downwash that is produced by eVTOL aircraft, particularly during arrival and departure at ground facilities, given that their rotors are characteristically quite small compared to those of more conventional, single-rotor helicopters.

Note though that there is evidence to suggest quite a strong influence of the Reynolds number in influencing the relative rates of growth of the short-wavelength instabilities along the vortices that tend to destroy their coherence, and the leap-frog instabilities that act to disrupt the wake on a much larger scale – bearing in mind that the rate of growth of the leapfrog instability is dependent on the coherence and effective strength of the vortices that are interacting to produce this dynamic. Indeed, where the vortices themselves become turbulent, the associated loss of internal coherence may alter appreciably the strength of the interaction between neighbouring loops of the wake and hence the rate of growth of disturbances to the overall structure of the system, adding an important element of variation into the wake structures that are produced by rotors with diameters that differ broadly enough for these effects to become important. The practical inferences from this analysis are such as to suggest extreme caution when comparing and correlating data for the downwash, and (as shall be shown shortly) by extension, the outwash, measured on model-scale rotors with those obtained from full-scale systems, and indeed to be careful in extrapolating too directly from established helicopter experience to the world of eVTOLs.

Note too that any equilibrium that is established within the downwash might potentially be disrupted when the wake reaches the ground and turns into an outwash. Following the same argument as presented earlier, the rate at which disturbances spread along the wake, being related to the loads produced on the rotor, is relatively unaffected by presence of ground, whereas the rate of convection of the disturbances away from the rotor is relatively strongly influenced by the way in which the velocity varies along the wake as it touches down and subsequently spreads out across the ground. Some of our calculations suggest that this alteration of the relative rates of spreading and convection of the disturbances can precipitate the flow that is produced by rotors with certain design characteristics (the specifics of which still remain obscure to us), when operating generally within a relatively narrow band of heights above the ground, into a topological state which might quite appositely be termed a 'ground-induced Vortex Ring State' as shown in Fig. 11. The flow with the rotor in this state is essentially toroidal and recirculatory in nature, and the rotor can be subject to the same sorts of fluctuations in loading (generally accompanied by a measurable reduction in the mean thrust of the system for given collective pitch setting) as when the VRS is encountered with the rotor in free air.

Fig. 11 shows the results of a numerical simulation of the flow, and the implicit challenge to the community is to try to detect the existence of this collapsed form of the wake in the real world. If such flows do exist, then the practical implications for the safety of rotorcraft flight would seem obvious – so, for instance, when assessing the safety of landing a multi-rotor aircraft on an elevated platform where not all rotors might simultaneously be at the same height above the landing surface. It is very tempting to consider the evolution of the wake simply as a one-way process, originating at the rotor and proceeding to completion in the far reaches of the fluid. The principal importance of this example, however, is that it reveals very clearly the elliptic nature of the relation between vorticity and velocity, particularly as embodied in the ability of disturbances to propagate upstream through the flow, and reminds us that the evolution of structure within the rotor wake is very much a bi-directional process that can, under certain circumstances, be driven exceptionally strongly by *downstream* influences on the system (*e.g.,* potentially by the presence of infrastructure, walls, *etc*. nearby on the ground).

6. THE FLOW IN THE OUTWASH BELOW AN ISOLATED ROTOR

The importance of this more nuanced view of the internal structure within the wake in terms of individual vortical structures and their inherent instability to small perturbations becomes apparent when trying to understand what happens when the wake below the propulsor makes contact, and subsequently interacts, with the ground.

The potentially somewhat pathological case shown in Fig. 11 notwithstanding, 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. The proposition that the structure of the flow might continue its progression from order towards disorder as the flow continues to develop out across the ground, once the downwash has reached the surface and has turned outwards to form the outwash, allows us to infer that the form of the propulsor's interaction with the ground might be affected very significantly by the distance of the propulsor above the surface 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 Fig. 12, where the analysis that was presented in Fig. 10 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.

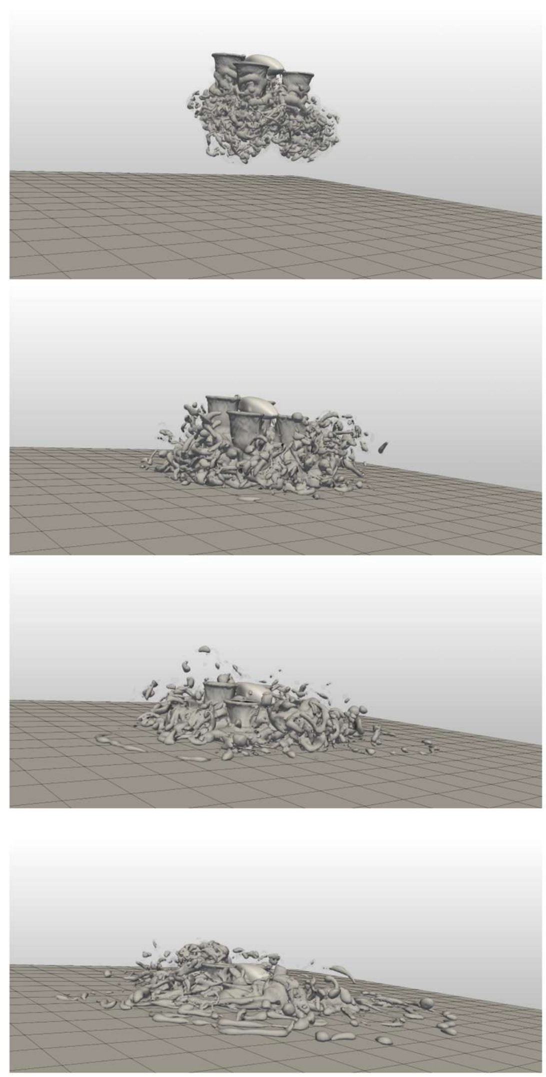


Fig. 13. The structure of the downwash and outwash that is produced by a quadcopter-like vehicle when hovering at various heights above the ground. The interaction with the surface below the aircraft takes on a different form, in similar fashion to that shown in Fig. 12 for an isolated rotor, depending on the height of the aircraft above the ground.

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 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 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.

The potential for a variety of different types of ground interaction is illustrated in more practical terms in Fig 13, which shows how the structure of the downwash and outwash produced by a relatively simple multi-rotor vehicle might change as its height above the ground is reduced. Indeed, the transition of the wake from having a relatively ordered structure near the rotors, 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 many of the images contained in this paper.

A crucial point to re-iterate in the present context is that the aerodynamic scaling parameter that governs the form of the interaction with the ground is the rotor diameter. 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 ties clearly into the argument regarding the extent out from the aircraft to which the outwash might evolve in any given form, and indeed lends insight into how the design of different rotorcraft might impact the properties of the outwash that they produce.

An important question then arises as to whether the disordering of the wake as it travels outwards across the ground is reversible or not. Two factors suggest that the process might indeed, in some sense, be reversible, and hence that (re-)intensification of the vortical structures on the ground (and hence also the associated velocity in the outwash) might be able to take place at quite some considerable distances

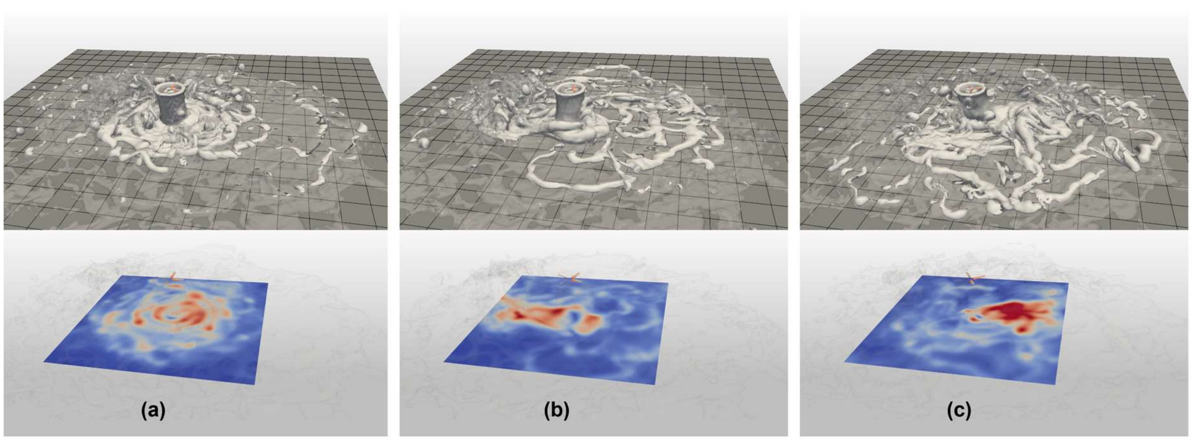


Fig. 14. Numerical simulations of the flow in the downwash and outwash below a four-bladed rotor in high hover above the ground. Top: instantaneous vorticity distribution in the flow. Bottom: instantaneous velocity just above the ground plane (red: highest, blue: lowest) at various times. The underlying geometric symmetry of the system is axial, but the flow is hardly ever observed to exhibit this symmetry itself (a). The system is more commonly observed in a state where this symmetry is broken, and the outwash instead jets out radially along a preferred axis – the direction of which changes slowly over time (b, c).

from the rotor. Firstly, stretching in the radially-directed flow out across the ground acts to align the vorticity circumferentially, encouraging the reformation of a distribution of vorticity around the rotor which is principally concentric in its orientation. Secondly, even a relatively homogeneous vortex sheet, once re-oriented in this way, appears to be subject to what seems to be a form of Kelvin-Helmholtz instability, which causes the vorticity to clump into a set of circumferential vortex waves (see Fig. 17). It might be imagined that, if this instability were to be allowed to run its course, the end product might be the re-creation of a set of compact vortices that are able to propagate out across the ground plane with renewed vigour and strength. The possibility of emergence of structure from disorder through secondary mechanisms such as this raises the potential that a range of flow features might arise on the ground plane that are not simply an evolution of structures that are already present when the rotor wake originally reached the ground and turned from downwash into outwash.

Now, a common mis-conception is that the underlying fluid dynamic equations, when supplied with boundary conditions that are symmetric in some way, should produce only solutions that have that same symmetry. This is emphatically not the case – it is often true that a set of less-symmetrical solutions to the equations are also possible, but that, for each symmetry of the boundary conditions that is not embodied in any particular solution that happens to be observed (or calculated), other solutions will exist that are related to the observed solution through embodying the broken symmetry. So, for instance, if the boundary conditions have left-right (mirror) symmetry and a right-handed solution is observed, then the mirrored, left-handed solution will also exist. We believe this potential for a multiplicity of solutions to the governing equations to be crucial in understanding the properties of the flow in the outwash that is produced by isolated rotors – and to perhaps an even greater degree in understanding the flows that are produced on the ground as a result of the aerodynamic interaction between multiple rotors, as will be discussed in the next section of this paper.

Indeed, the potential for symmetry-breaking can manifest in a variety of ways within the outwash. The basic principle is that a flow that initially exists with a higher degree of symmetry can (and usually will) break down under the action of its inherent instabilities into a state that has fewer symmetries.

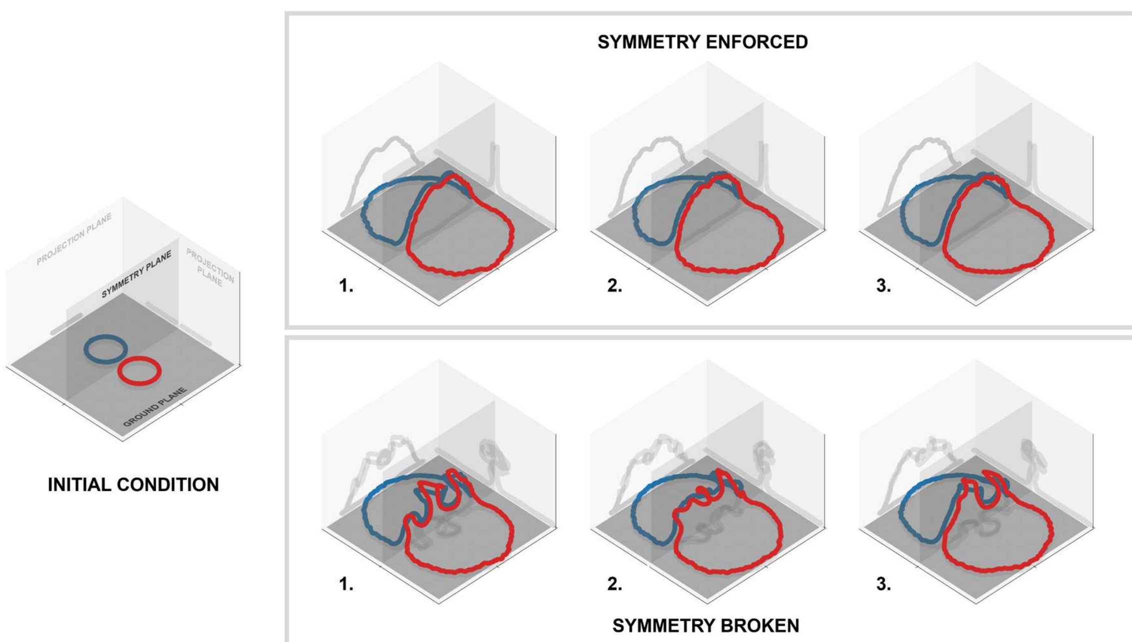


Fig. 15. A model for symmetry breaking in the flow that is formed in the outwash below multiple rotors. The evolution of two opposing vortex rings is tracked from starting conditions that differ only by the addition of a small amount of random noise. If the lateral symmetry of the system is (artificially) enforced (top) then the subsequent state of the system is essentially predictable. If the system is allowed to evolve naturally (bottom), the lateral symmetry of the system is destroyed and it becomes difficult to predict the subsequent evolution of the system.

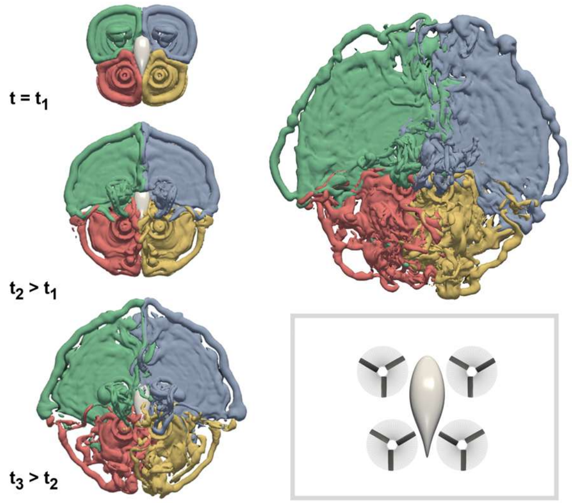


Fig. 16. Numerical simulation of the development of the flow below quadcopter-like vehicle when hovering at low altitude above the ground. The wakes produced by each rotor are coloured differently to show more clearly the symmetries within the system. At left, the progression of the wake during its initial development is shown. The symmetry of the initial state of the flow ($t<t_1$) is unstable, and is very quickly broken to form a much more complex flow ($t>t_3$). At right, the configuration of the flow at a much later stage in the development of the outwash is shown: additional structure on all scales has emerged as a result of the system's continued evolution in the presence of its inherent vortical instability. (Images from Ref. 3.)

The consequences for the state (or variety of states) in which the flow in the outwash might be observed are profound. The path taken during the evolution of any flow that is subject to an inherent instability is sensitive to any small perturbations of the system, and the fact that these perturbations might be immeasurable or random means effectively that, in practice, we lose a great deal of predictability regarding the state in which the system might be encountered at any particular instant, or indeed with regards to any final state that it might adopt in the longer term. In some instances, even though the system might be able to regain, temporarily, at least a semblance of its lost symmetry, the inherent instability of the system in that configuration will cause the symmetry to disappear again after further time has elapsed. Presence of bias in the system (*e.g.*, due to wind) can ensure that many of the inherent symmetries of the system will not actually be observed in practice, and, indeed, in the presence of larger-scale disruptions and perturbations to the system, for example when significant atmospheric turbulence is present, the inherent symmetries of the system can be destroyed so quickly that they might not ever be observed in practice. Indeed, in these circumstances, the progression of the structure of the wake through the orderly cascade described earlier may be supplanted during the early evolution of the system by an altogether more abrupt process.

Symmetry-breaking is such a pervasive feature of our simulations of rotorcraft outwash that we believe this process to be fundamental to the evolution of the structure of the flow produced below the rotorcraft, no matter if the aircraft has one or multiple rotors. As an illustrative example of the occurrence of symmetry-breaking in the flow below an isolated propulsor, the flow that is generated by a single, four-bladed rotor hovering at appreciable distance above the ground is shown in Fig. 14. The geometry of the system has approximate axial symmetry about the axis of rotation of the rotor – noting of course that the direction of rotation of the rotor imparts a 'handedness' to the vorticity distribution so that the underlying symmetry of the flow in the outwash is actually spiral rather than axial. Any period during which the structure of the outwash out across the ground actually embodies this underlying symmetry (see Fig. 14(a)) tends to be rather short-lived, however. Indeed, the wake very quickly tends to lose any axial symmetry that it might originally have had, skewing to one side so that the flow near the ground, instead of flowing out radially in a pattern that is itself broadly axially-symmetric, tends to concentrate along one particular radial axis (see Fig. 14(b)). The qualitative analysis presented earlier implies however that no particular axis along which the velocities out across the ground might concentrate in this manner should be privileged with respect to any other. Indeed, the 'choice' of axis is dependent on the precise nature of the initial perturbation that led to the growth of the disturbances to the wake to finite amplitude; the infinitesimal or random nature of these initial perturbations then implies that the breaking of the system's axial symmetry could result in the outwards flow being concentrated along any direction whatsoever. Interestingly, two possibilities then exist for the long-term behaviour of the system. The first is that a quasi-equilibrium is reached with the wake settling irrecoverably into a state with broken axial symmetry in which the flow jets out across the ground in one particular direction. This does not seem to be the case here – although the very slow development of the flow when in this mode renders the resolution of multiple such re-configurations very challenging for any current numerical method to resolve, the size of the fluctuations to the structure of the wake near the point at which the downwash turns to outwash seems to be large enough to drive a slow progression through the various possible orientations of the jet (Fig. 14(c)). Given sufficient time, and in light of the discussion above, the system should in fact be expected to cycle in this manner through all possible orientations of the jet, and in so doing, of course, axial symmetry should be restored to the long-term mean of the velocity distribution out across the ground in similar fashion to that shown in the left-hand panel of Fig. 4. The essential point though, harking back indeed to the motivation for this paper, is that any such ‘mean flow’ has very little relevance to the actual state of the velocity distribution within the system at any particular instant, and hence that quantifying the system in terms of this mean would be of questionable value in understanding the outwash from the point of view of the safety or integrity of personnel or objects immersed within the flow.

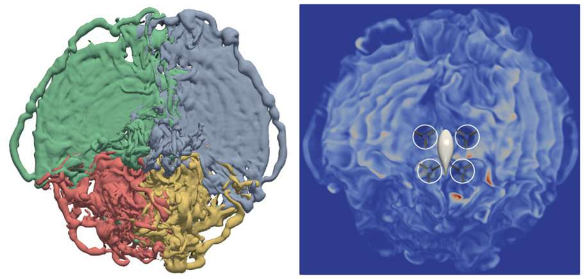


Fig. 17, showing the formation of vortex waves in the outer reaches of the initially flat, thin sheet of flow produced out to the front of a quadcopter-like vehicle when hovering at low altitude above the ground. It is possible that the formation of these waves is the early stage of a process that might lead (in some circumstances yet to be fully understood) to the re-intensification of the velocities in the outwash at unexpectedly large distances out away from the rotorcraft.

7. THE FLOW IN THE OUTWASH BELOW MULTIPLE ROTORS

Our simulations suggest that symmetry-breaking plays an even more important role in the development of the outwash across the ground below a system that has multiple rotors. A model for the basic physics is illustrated in Fig. 15, where the dynamics of a pair of vortex rings is shown. These rings might represent opposing elements of the structure of the vorticity distribution in the outwash between two neighbouring rotors, for instance, and, indeed, the basic idea behind the simulation is that the dynamics of the rings, as they interact with themselves and with the ground plane beneath, might represent some of the salient aspects of the evolution of the flow in the outwash of a system such as this. The initial condition of the system is as shown at left. Each ring has the same radius, lies initially at the same height above the ground plane, and (initial) mirror symmetry of the system is imposed by having the vorticity in one ring rotate in the opposite sense to that in the other. The geometry of the rings is perturbed by adding a very small amount of random, short-wavelength noise, and the system is then allowed to evolve according to Eq. (1). The diagrams at right are arranged to show three different manifestations of the geometry of the system at *the same* later time – in other words, each of the geometries that is shown is produced from the same initial condition save for a different distribution of small initial perturbations to the system. In the set of solutions shown at the top of the diagram, mirror symmetry is enforced for the duration of the simulation. The observed deviation between the different solutions is relatively small – continued imposition of the symmetry, no matter how artificial such continued imposition might be, can be thought of as enhancing the geometric stability of the configuration. The diagrams at the bottom of the same figure show the same state of affairs but where the lateral symmetry is not enforced as the vortex rings evolve. In this case the inherent instability of the fluid mechanics in the presence of internal noise causes the mirror symmetry to be broken very quickly, and the rings to evolve from effectively the same initial configuration into configurations that differ substantially from each other, but in an essentially unpredictable and random way (at least in the absence of a detailed specification of the initial perturbations that were applied to the system) as time progresses.

The important point is that the macroscopic differences in the sequence of configurations adopted by the system during its evolution, or indeed the eventual configuration of the system, should this be a meaningful concept, could not have been predicted in any comprehensive way from prior knowledge of the system (*e.g.,* knowledge of its initial conditions). Indeed, the sort of symmetry breaking illustrated in this simple example is often seen in simulations of the evolution of the wake of multi-rotor systems, raising important questions regarding the predictability of the flows in the outwash below multi-rotor aircraft in anything but the most general of terms.

As a more concrete example, Fig. 16 shows the early stages of the evolution of the wake below a representative quad-rotor aircraft, hovering at relatively low height above a flat ground plane. To aid interpretation of the figure, the vorticity produced

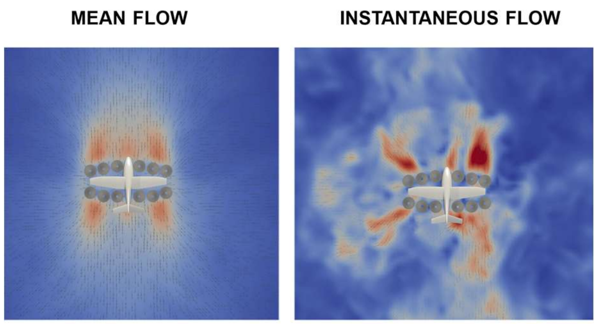


Fig. 18. Comparison of numerically-simulated time-averaged outwash velocity for a multi-rotor eVTOL aircraft (left) with a snapshot of the instantaneous velocity within the flow (right). The traditional characterization of the outwash as a steady flow with superimposed fluctuations encapsulates very poorly the discrete and pulsatile nature of the flow, and underestimates significantly the distances out from the aircraft to which the velocities in the outwash might be appreciable.

by each rotor of the system is separately coloured. In the simulation, the rotors are started impulsively, and, in the images at left, the ring-like starting vortex that is created by each of the rotors during the initial stages of the development of the downwash below the vehicle can be seen quite clearly. These vortices travel down towards the ground, then spread out across the surface, growing in diameter and leaving the developed flow in the outwash behind them. Traditionally, when simulating such flows, one waits for long enough for these starting vortices to have travelled out to appreciable distance from that part of the flow near the aircraft that is of interest before considering the flow to be 'representative' or 'established'. Although this might be possible in simpler cases (for example when only a single rotor is involved) the images shown in Figure 16 reveal how intimately these starting structures govern the subsequent evolution of the flow, and indeed how the starting structures tend to remain, perhaps even as an integral part of the flow, over its entire time of existence, never in fact being swept out to distances far enough from the system for their effect to have disappeared entirely from the analysis.

The system initially exhibits a great deal of the symmetry that is endowed to it by the arrangement of its rotors, but over time this symmetry breaks down, through much the same mechanisms as shown in Fig. 15, to yield a far more complex pattern of flow out across the ground. The right-hand image in Fig 16 shows the structure of the outwash below the vehicle once the flow has evolved for quite some time. Although echoes of the original symmetry remain, the still image does little justice to revealing how the flow along the forward axis of the aircraft is able to meander considerably from side to side, crossing backwards and forwards over the longitudinal plane of symmetry of the aircraft as it does so. Indeed, the interaction between the vortical structures that are produced on either side of the interface between the flows produced by the rotors on opposing sides of the aircraft is associated with the formation of narrow jets in which the flow is extremely unsteady and the instantaneous velocity out across the ground can be very high (see Ref. 3 for a more detailed description of this dynamic.) It is interesting to note that the flow behind the vehicle is qualitatively very different to the flow out in front – the slightly greater elevation of the rear rotors above the ground than the front rotors, given this particular aircraft's configuration, causes a turbulent, deep outwash to be formed behind the vehicle as a result of the 'stacking' of the outwash from the rear rotors on top of the rearwards-running component of the outwash from the front rotors. By comparison, the outwash from the forward rotors, as it runs out ahead of the aircraft, is much thinner and sheet-like than that produced to the rear of the aircraft. It is perhaps worth reinforcing the point that not every unexpected lack of symmetry in the flow is a consequence of symmetry breaking, and indeed it should be obvious that this last effect arises simply in response to a blatant asymmetry in the geometry of the aircraft itself!

Fig. 16 shows the structure of the flow that is produced by a vehicle that has relatively simple configuration, but much the same dynamics is seen when the vehicle has much more complex geometry. Fig. 18, for instance, shows the predicted distribution of velocity on the ground below a vehicle with twelve rotors, all mounted sufficiently high above the surface that their wakes are already considerably disordered by the time that they reach the ground and contribute to the outwash below the vehicle. As shown in the left hand image in Fig. 18, when the velocities in the flow are averaged over many hundreds of rotor revolutions, the flow appears to exhibit at least some of the underlying geometric symmetry of the vehicle, but, as in the very much simpler case of the conventional helicopter shown in Fig. 4, this temporal average bears very little relationship to any instantaneous manifestation of the flow, one example of which is shown in the right-hand image of Fig. 18. In the light of recent insights[4] into the physiological effect of the outwash on humans that might be immersed in the flow, it is worth recalling at this point that, although our historical focus has largely been on quantifying the outwash to the level of detail shown in the left-hand image of figures such as Fig. 18, proper quantification of the hazards posed by the outwash will in all likelihood require knowledge of the system to the level of detail shown in the corresponding image at right.

When considering the analysis just presented, the question naturally arises then whether the distribution of velocities in the outwash that is observed in the long term is unique to the aircraft configuration, or, in other words, if, by say some accident of its early history, the flow might have evolved into an entirely different state. In pure numerical or mathematical terms, we wish to know whether the observed state of the system (especially in the long term, once the effects of obvious initial differences have had time to dilute) is independent of the conditions under which the flow was started. In real terms, we may need to ask if the same downwash pattern is produced after landing the aircraft as is produced after starting the motors on the ground, or, in terms of practical measurement of the properties of the outwash, whether the outwash is 'the same' in any meaningful sense after rotating the aircraft through a finite angle during an azimuthal sweep, or while stepping through a finite set of hover heights. The analysis presented above should perhaps raise some doubts in this regard.

Indeed, some early results from our simulations would suggest that extreme care should be taken, lest specific measurements of the outwash be over-generalised or treated without the necessary circumspection as to how all-encompassing and representative of the qualities of the aircraft being examined the data actually is. Figure 19 shows two qualitatively different solutions, obtained for the same counter-rotating, two-rotor system in each case, but where the only difference was the set of initial conditions from which the simulations were allowed to develop. The system shown at left was started impulsively. Even after several hundred rotor rotations, the confluence between the rotor wakes aligns reasonably closely with the original plane of geometric symmetry of the twin-rotor system, and the structure of the outwash produced by the two rotors continues to manifest, at least statistically, the mirror symmetry of the geometry of the system.

The system at right was perturbed by rotating the rotors through a small angle a short way into the simulation, thus breaking any direct connection to the evolutionary path already followed by this system from its identical starting conditions to the system already described. Although it was expected in this case that mirror symmetry would re-establish

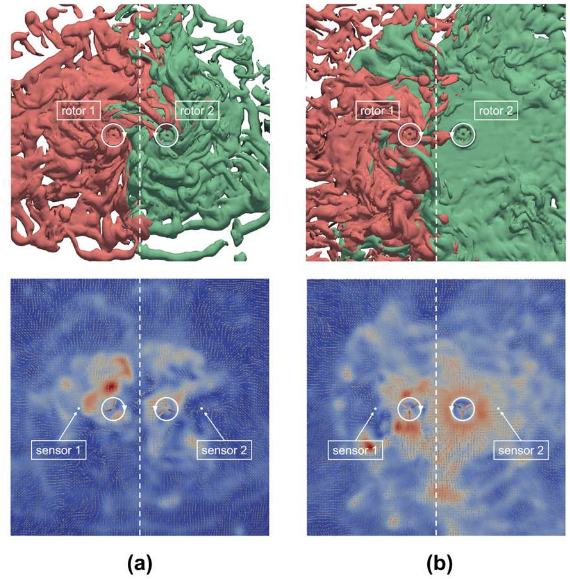
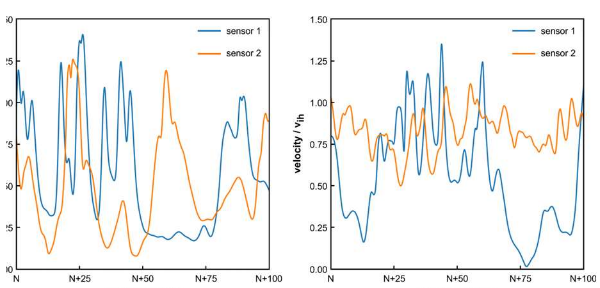


Fig. 19. Numerical simulation of the flow below two identical, counter-rotating rotors hovering at the same height above the ground. The vorticity distributions (top) and snapshots of the instantaneous velocity distribution just above the ground (bottom) are for simulations of the system that differ only in their starting conditions, yet large qualitative and quantitative differences in the flows are able to persist for the duration of calculations that in each case captured a thousand rotor revolutions'-worth of data.

itself given sufficient time, this restoration had still not taken place when the simulation was halted some several hundreds of rotor revolutions later. Instead, the system remained in a lop-sided state, with the wake (coloured in green) from the right-hand (counterclockwise rotating) rotor adopting a sheet-like, high-velocity form, displacing the wake (coloured in red) from the left-hand (clockwise rotating) rotor a considerable distance from the plane of symmetry and causing it to roll up into a turbulent, highly-unsteady and deep outflow across the ground.

The effect of these differences on the velocity distribution on the ground is clearly evident in the bottom images in Fig. 19. As shown in Fig. 20, in case (a), the character of the velocity as measured at a given distance out to the right of the pair of rotors has very similar statistics to that measured at the same distance out to the left of the rotors, as would be expected given the qualitative similarity in the structure of the outwash that is generated by both rotors in this instance. This is not the situation for the flow illustrated in case (b) – the velocities measured out to the right have higher mean speed and significantly less variability than those measured out to the left of the system. Besides raising important theoretical questions, simulations such as this suggest that we may need to be particularly careful with regards to any implicit assumptions we might be tempted to make when considering the independence of any set of measurements of the instantaneous state of the system from the details of its earlier history.

Returning finally to the idea that the dynamics of the inherent instability of the wake is essentially convective in nature, we can use this example to infer that the time taken for the flow to refresh in the presence of the inherent vortical instability of the wake, for instance when attempting to use an azimuthal sweep to characterize the velocities in the outwash, might not only be a function of the time taken for the vortical structures to wash out of the region of interest and to be replaced with a flow that is representative of the new state of the aircraft (the time needed for this process to complete being proportional to the distance away from the aircraft at which the measurements are being taken divided by a suitable measure of the average speed of the flow in the outwash) but also for disturbances associated with the older flow no longer to reach the point of interest. This is an obvious consideration if the vortical structures produced in the outwash are able to slow down and persist in the far field, but, even where the convective mechanism is fully effective, it should still be remembered that continued back-propagation of the disturbances towards the rotor (a subject touched on earlier) can profoundly extend the time for which the flow in the outwash remains affected by the state of the system at earlier times. These brief comments hopefully will serve as a warning to those about to embark on measurement



(a) (b)

Fig. 20. Time-histories of the velocities as measured at the sensor locations shown in Fig. 19 for numerical simulation of the flow below two identical, counter-rotating rotors hovering at the same height above the ground. Plots (a) and (b) are for simulations that differ only in their starting conditions, yet the differences in the resulting velocities are clearly apparent.

campaigns in the near future, but given the limits of space in an already-long paper, fuller discussion will be deferred to a later work.

8. PRACTICAL IMPLICATIONS

How we go about characterizing the velocities in the outwash field that is produced by an eVTOL aircraft when operating close to the ground is a topical area of current concern to the manufacturers, the potential operators, and the regulators of eVTOL aircraft alike. Regulators are becoming increasingly aware that provisions might need to be made to protect nearby infrastructure and bystanders from the hazards that are posed by the flow velocities to which they might be subjected. If serious mis-characterization of the potential hazard is to be avoided, it is essential that the basic properties of the outwash field are understood so that the procedures that are eventually adopted to quantify the velocities that are produced in the flow beneath these new vehicles are properly framed.

In this vein, it might be tempting, at least in some quarters, to dismiss many of the observations made in this paper as unapplied or merely of theoretical interest. It is true that we have dwelt at length on various abstruse concepts, such as the uniqueness of solutions, the role of accidents of history in governing the final state of the system, and the profound effects of small perturbations in bringing into question the predictability of systems that are inherently unstable. These topics are not traditionally viewed as within the purview of 'practical' engineers.

It is true also that much of the argument up to now regarding the characterization of the outwash that might be produced by multi-rotor vehicles has focused around the minutiae of sensor placement, density and frequency response. These are indeed salient issues, but we need to base our reasoning around these important issues on a comprehensive and fundamentally correct understanding of the properties of the system. If, for example, we believe that the velocity field is radially-symmetric and that its statistics are time-invariant (perhaps based on our conceptualization of the outwash being similar to that of a helicopter – see Fig. 21) then we might be tempted to characterize the outwash of our eVTOL aircraft using simple, linear arrays of sensors extending out from the aircraft along a few, arbitrarily chosen, azimuthal axes. It is only through conceptualizing the outwash field of these vehicles in terms of a much more complex spatial and temporal variation of the velocity that we might be motivated to introduce a more spatially comprehensive sensor array. Indeed, some of the results presented here and in the supporting literature show just how varied the outwash patterns can be for aircraft with different configurations – to the point that the ideal, popularized in some quarters, of a ‘one size fits all’ sensor array may be a complete chimera.

Some of the inherent characteristics of the outwash that are hinted at in this paper may be indicative however of a set of even more fundamental issues that might need to be addressed before we are able to quantify with any confidence the risks that might be posed to infrastructure and bystanders by the outwash that this class of vehicles will very likely produce during the course of their operations.

The idea, for instance, of rotating the aircraft on various headings with respect to a fixed sensor array on the ground in order to capture the azimuthal variation of outwash velocity around the aircraft is close to being accepted as the strategy of choice – and seems at face value to be eminently sensible, even if the only motivation is to save on the costs of a more comprehensive sensor array. It is important though that the validity of this approach is considered in the light of the time taken for the flow to re-establish itself in a representative, quasi-steady state while the transients in the flow field following the re-orientation of the aircraft wash out into the far field. The timescales associated with this process are as yet poorly understood. We know from our numerical simulations that this equilibration process is, for the greater part, mediated by the dynamics of the large, relatively slow-moving vortical structures that comprise the outwash field, but we can also extrapolate from simpler instances to foresee that the minimum required ‘refresh time’ between batches of sensor readings, if the measurements are to be properly representative of the state of the aircraft, might also be influenced by the rate at which any *disturbances* caused by these structures are also able to propagate out of the domain of interest. It is likely thus that, in most instances, a great deal more care than is perhaps currently appreciated will need to be taken during any particular measurement campaign to allow transients within the flow field to dissipate between successive measurements.

We have shown results too that suggest that the system may never revert to a state that is truly independent of its earlier history, rendering open the particularly tricky question of whether it is indeed possible to extract an unique velocity ‘signature’ that can be defined robustly enough to encapsulate the threat posed by the aircraft – and thus to allow for rigorous and confident certification of the vehicle.

Given the urgency of the situation and the various pressures to “just do something” from various parts of the VTOL community, it is hard not to adopt a mentality of “let’s just go out and measure and see what we find,” but such an approach to the problem stands the very real risk of being wasteful of scarce resources and, when all is said and done, inherently futile. The analysis presented here will hopefully remind the community of the value of first framing any such experimental campaign in terms of how the real world might be expected to behave – and then in exploiting our expectations of the real world in terms of a hypothesis that can be used, formally, to define what we want to measure and why. The process leading to the discovery of the Higgs boson[19] forms the perfect analogy – this particle would never have been discovered if the experimentalists had not known what they were looking for and, at least roughly, where to find it. We need to come up with the equivalent theoretical underpinning in our own domain if waste is to be avoided, and, potentially, if lives are not to be endangered while we expend our efforts on unconstrained and uninformed data-gathering.

9. CONCLUSION

The history of the study of rotorcraft aeromechanics is surprisingly short, and, as is the case with most other scientific disciplines, the more we investigate, the more we seem to realise that we have still to learn. For the most part, at least up to now, we have been interested (with notable exceptions – for instance in the study of the origins of the Vortex Ring State) in understanding the behaviour of vehicles when the flows that they produce are still in a reasonably ordered state (for instance when estimating rotor loads, vibration, acoustics, *etc.*). Confining our efforts to understanding this highly constrained yet comfortable sub-domain of problems is no longer sufficient if we are to address the exigencies of the modern rotorcraft industry, and in particular if we are to overcome some of the challenges that will be posed if or when electric VTOL aircraft enter into public service.

The problem of understanding the flow within the outwash, at least to the level required to be confident of the safety of the passengers who will use these aircraft – as well as of the bystanders who, intentionally or unintentionally, will be affected by their presence – is perhaps one of the most difficult that the rotorcraft community has ever had to address. To understand the properties of the outwash field below the vehicle, we need to understand the behaviour of the flow when it exists on an extremely sensitive middle ground – in an intermediate state, caught between order and disorder, where the vagaries associated with the rotor wakes' own inherent instability poses a distinct impediment to the encapsulation of its properties in any but the most ephemeral of ways. Proper and robust quantification of the risks associated with the outwash that is produced by any one of these aircraft thus poses distinct problems to the theoretician – who would like to encapsulate the physics in compact and accessible form, to the numericist, – who cannot be sure that their spot-calculation conforms robustly to any physically-representative real-world situation, or that their solutions are not contaminated by the properties of the numerical algorithm used to generate them, as well as to the regulator, who may not be able to rely on the consistency of the behaviour of the system that they are trying to quantify – at least not to the extent of being able to construct conservative but fair principles against which to certify these aircraft.

How then do we proceed? Can we design analytic techniques that are robust to the vagaries inherent in the knife-edge nature of the evolution of the system in the presence of these instabilities, where vanishingly small differences seem to be able to manifest in radically different outcomes as time progresses? We do not yet know enough to answer this question with any degree of certainty. Instead, we have presented some evidence to suggest that our ability to quantify the properties of *the* outwash of any particular rotorcraft system might be rather limited (should a meaningful interpretation of this phrase even exist) even though our ability to understand the governing physics may not.

Although modelling the properties of the outwash may be, by far, one of the most challenging exercises in rotorcraft aeromechanics, are we at the end of the road as far as our current batch of numerical techniques are concerned? How might we adapt our current analyses to address challenges such as those posed by the outwash issue, as well as perhaps by the many other challenges emerging from this nascent technical field as it advances into areas that, although they might seem familiar to us in many respects, are very much on the fringes of our current understanding? It is all too easy to adopt an overly naïve approach, to gloss over the inherent complexities of the problem that we face, and to proceed regardless using our

Fig. 21. Real-world characterization of the outwash below an eVTOL aircraft will be prone to significant error, especially if the complexity of the underlying physics is not fully appreciated. (Image from Ref. 5.)

well-worn tools and techniques. Or, instead, we can square up to the challenges that face us. Although a great deal of humility in the face of the complexity of the physics may be in order, there is a real chance here to re-juvenate our understanding of rotorcraft aeromechanics, to advance our knowledge into areas of flow physics that have been neglected for far too long, and, in the process, to advance significantly our understanding of the basic science on which our discipline ultimately relies.

It is hoped that this paper will make a strong contribution to this effort by revealing some of the complexity, as well as some of the inherent beauty, of the physics that we are up against – and in so doing will contribute to improving the safety of this new and developing form of air transport.

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11. CONFLICT OF INTEREST

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"The work of a pioneer in science of technique often consists of finding a correct solution, or creating a working mechanism, based on laws that are not yet discovered."

Igor Sikorsky (1889-1972)