ROTORWASH OPERATIONAL FOOTPRINT MODELING

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Wind or "rotorwash" generated by rotors, ducts, or jets affects the operational suitability and utility of future Vertical Take-Off and Landing (VTOL) aircraft. This paper presents the assessment process, environmental limits, rotorwash modeling, and output display supporting the rotorwash operational footprint model. These elements graphically combine to display the rotorwash operational impact assessment on the ground environment as contour plots or "footprints." The tools and methodology developed were for the single main rotor helicopter, tandem helicopter, and tiltrotor configurations, but can be extended to encompass additional configurations. The rotorwash operational footprint displays the effect of winds generated by rotor thrust on the surrounding environment. These footprints can be used to evaluate compliance with aircraft performance specifications, verify safe separation distances, or influence trade studies. Future military VTOL aircraft must have a rotorwash footprint that enables mission requirements to be safely accomplished. The influences of these key factors for safe operation are captured as a suggested performance specification for future military VTOL aircraft.

SYMBOLS AND ABBREVIATIONS

AGL	Above Ground Level
CDA	Concept Development Activity
CHARM	Comprehensive Hierarchical Aeromechanics Rotorcraft Model
dA/dy	Change in Area with Respect to Height
deg F	Degrees in Fahrenheit
DL	Disk Loading
DoD	Department of Defense
ft, FT	Feet
fmax	Maximum Peak Outwash Force
GTOW	Gross Take-Off Weight
H/R	Height / Rotor Radius
inc. area	Incremental Area
JHL	Joint Heavy Lift
lb	Weight in Pounds
LZ	Landing Zone
MILVAN	DoD 20 foot Shipping Container
MMBV	Mean Minimum Breakage Velocity
mph	Miles per Hour
NAVAIR	Naval Air Systems Command
PAXman	Human Wind Drag Reference Area
q	Dynamic Pressure
RoWFoot	Rotorwash Computer Program
VTOL	Vertical Take-Off and Landing
WOD	Wind Over Deck

EXECUTIVE SUMMARY

Wind or "rotorwash" generated by rotors, ducts, or jets affects the operational suitability and utility of future Vertical Take-Off and Landing (VTOL) aircraft. As aircraft physical size, weight, and disk loading increase beyond the range of current systems, the risk increases that rotorwash operational impact(s) may compromise an aircraft's ability to satisfy the warfighter's needs. Early definition of anticipated rotorwash flow field characteristics will permit an assessment of operational suitability and determine whether specific design changes are warranted and/or if acceptable operational tactics, techniques, and procedures can be established.

This paper documents the assessment process, environmental limits, rotorwash modeling, and output display supporting the rotorwash operational footprint model. These elements graphically combine to display the rotorwash operational impact assessment on the ground environment as contour plots or "footprints". The tools developed are for the single main rotor helicopter, tandem helicopter, and tiltrotor configurations, but can be extended to encompass additional configurations. The rotorwash operational footprint displays the effect of winds generated by rotor thrust on the surrounding environment. These footprints can be used to evaluate compliance with aircraft performance specifications, verify safe separation distances, or influence trade studies.

The assessment process utilizes “scenarios” to describe the bounding conditions within the operational space. Each scenario contains a description of the aircraft flight state and environmental conditions. Together, the scenarios bound the evaluation of the operational space for a wider range of envisioned missions.

The surrounding environment is quantified by limits associated with rotorwash velocity, force, and energy on personnel, structures, and materials. Military personnel limits are associated with the strength capabilities required to overcome rotorwash generated drag forces and tolerance to physical injury due to flying projectiles. Structural limits are associated with the magnitude of wind velocity (dynamic pressure based) required to damage surrounding buildings, shelters, and tents. Material limits are referenced to property damage caused by flying projectiles. An additional advisory limit is recommended for a heliport or airport location and for landscaping as based on dynamic pressure.

Prediction of the wind velocity in the rotorwash flow field utilizes a momentum based conceptual model that is empirically tuned using flight test data. This model is implemented in the computer program, RoWFoot. An attempt to utilize a high fidelity tool to extend verification of RoWFoot beyond the range of existing flight test data was unsuccessful. RoWFoot should be verified beyond the range of existing flight test data using a physics-based model. In the absence of this verification, the confidence in the tuned momentum-theory model is reduced where it extrapolates outside the bounds of correlated flight test data.

Velocity and drag force footprints were generated using RoWFoot results for each operational scenario. Velocity based outwash footprints display the maximum magnitude of wind velocity in the outwash. Force based outwash footprints utilize the PAXman anthropometric model to determine the drag force on personnel for a given height-velocity profile. Both types of outwash footprints display relevant environmental limits as contour lines on a topographical plot. These footprints allow for “visualization” of the ability of a VTOL aircraft to safely conduct warfighter missions as influenced by rotorwash effects.

Future military VTOL aircraft must have a rotorwash footprint that enables mission requirements to be safely accomplished. Key factors that have the ability to significantly influence the aircraft design or operational envelope are:

- Ground personnel capability limits during external load operations
- Shipboard equipment limits
- Landing zone separation required during single or multiple aircraft operation

The influences of these key factors are captured as a suggested performance specification for future military VTOL aircraft. The text of this specification is as follows in italics:

Rotorwash shall permit operations up to operational capability limits without endangering, damaging, or exceeding physical capabilities of personnel, equipment, or structures. Specifically the rotorwash shall allow safe operation during:

- *Ground and air taxi maneuvers*
- *Operations from an unprepared landing zone with internal and external loads*
- *Shipboard operations with internal and external loads during air operations*
- *Airborne operations including hoist, fast rope, air-to-air refuel, and air drop*

This technical paper summarizes the rotorwash operational footprint modeling with the associated assessment process, environmental limits, rotorwash modeling, and output display to verify compliance with the first two of the four bullet points of the suggested performance specification. The third bullet requires shipboard equipment limits to be specified. The paper also provides a limited amount of operational insight to the fourth bullet point.

1. INTRODUCTION

Utilization of VTOL aircraft may be limited by their impact on the surrounding environment. The wake produced by a thrust-generating rotor can have nuisance to hazardous level effects on ground personnel, structures, and equipment as well as negatively affect airborne operations.

Rotorwash is defined as the overall velocity flow field produced by a rotor or other thrust generating device. Regions within the rotorwash include “downwash”, “transition”, and “outwash”. Downwash is the vertical component of the rotorwash flow field under the rotor(s). In the transition region, the downwash contacts the ground plane, turns, and becomes outwash. Outwash is the horizontal component of the rotorwash flow field outside of the area under the rotor(s). Figure 1-1 graphically displays the rotorwash under both a hovering single- and twin-rotor aircraft.

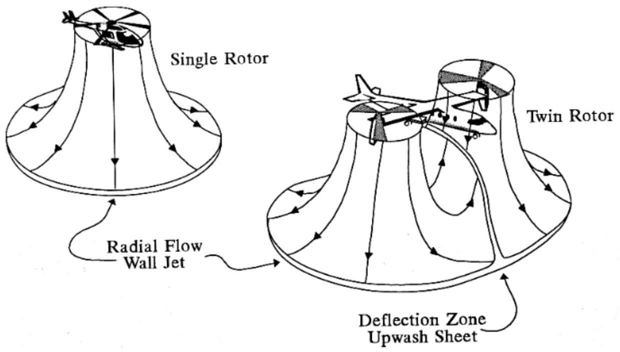


Figure 1-1 Rotorwash Flow Fields of Single- and Twin-Rotor Configurations Operating in Close proximity to the Ground [1]

The downwash primarily impacts operations directly under the aircraft such as airborne operations. Outwash primarily impacts the ground area surrounding the aircraft. Impact of the outwash on the surrounding environment can be represented as an operational footprint. This footprint defines the landing zone clearance requirements such as separation from structures, unprotected people, other aircraft, and shipboard equipment. The footprint also aids in visualizing the ability of ground personnel to approach and depart the aircraft.

1.1 Purpose

Quantification of the outwash impact supports the development of future aircraft requirements and specifications. This quantification methodology and the associated limits can be depicted as a footprint the aircraft will have on its operational environment. Prediction and display of the outwash footprint on the ground environment allows visualization of the potential impact that current and future aircraft may have on military operations.

This paper documents a methodology used to evaluate future concepts for their outwash footprint and is an evolution of previously used methodologies. The documentation includes evaluation conditions, environmental limitations, modeling methods, and a footprint display method. These methods and limits can be used to support future aircraft development.

A conceptual analysis tool predicts the rotorwash velocity flow field. When used in conjunction with appropriate environmental limits, post processing allows generation of an outwash footprint to produce topographical-like plots of the VTOL operational impact on the ground environment. This ground environment includes personnel, structures, landscaping, and equipment.

1.2 Background

During the Joint Heavy Lift (JHL) Concept Development Activity (CDA), there were concerns that large VTOL aircraft would limit operations in the ground environment. Past experiences with tilt wing, fan-in-wing, and jet lift aircraft documented issues with the wake eroding ground surfaces and prohibiting operations under the aircraft. Experiences with larger Department of Defense (DoD) rotorcraft, including the CH-53 and V-22, suggested increasing rotor size and loading could prevent future platforms from being used in some operational environments.

This study was initiated to determine the performance-based operational limits related to rotorwash of VTOL aircraft. Results are intended to influence future VTOL rotorwash performance based requirements.

An analysis and modeling capability for prediction of the outwash operational footprint was developed to support this study. This paper is a summarization of the results of the extended study [2,3] that originated with the JHL CDA. The resultant capability enables evaluation of the rotorwash operational impact of both current and future VTOL aircraft.

1.3 Approach to Modeling Environment

The developed modeling approach combines rotorwash flow field analysis with environmental limits. This facilitates production of operational footprints for hovering VTOL aircraft. These operational footprints appear as topographical-like plots that are used to visualize the effect the aircraft will have on the ground environment. These plots represent the rotorwash flow field in terms of the impact (limits) on the surrounding environment. These plots also define the distance from the aircraft required for safe operations.

The modeling approach leverages and extends previous efforts in analyzing and modeling the rotorwash flow field. This approach uses a combination of conceptual level modeling and high fidelity modeling. Modern computer systems and data visualization have enabled refinement beyond the previous state of the art for rotorwash prediction and analysis. High fidelity modeling is slower, more expensive to execute, and requires a more complete geometric description of the aircraft than conceptual level modeling, but it has the potential to capture the flow field qualities outside the scope of the test data. After correlation to test data, the high fidelity modeling was used to provide an extended set of values for correlation of the conceptual modeling. This extension included quantitative sets for height above ground, disk loading, and azimuth angle around the aircraft. Unfortunately, discrepancies within the high fidelity modeling results did not allow the conceptual level modeling to be confidently extrapolated outside the boundaries of the available quality flight test data. Therefore, the conceptual level modeling cannot be considered verified outside these limits.

Human performance and environmental limits were derived from literature search results and NAVAIR performance testing of military personnel. The literature search produced limits associated with personnel, terrain, structures, landscaping, and equipment. Human performance testing increased the scope and sample size of known personnel limits associated with outwash environments.

2. OPERATIONAL EVALUATION PROCESS

This section defines the evaluation cases and associated parameters to the rotorwash operational model. The evaluation cases describe the assessments to be completed. Within each evaluation case, the aircraft and its operational environment are defined by sets of parameters that serve as modeling inputs. Values for these inputs define the aircraft and the operational limits associated with the rotorwash in the surrounding environment. These limits are then used in conjunction with the flow velocity modeling to generate an operational impact footprint for an evaluation case.

2.1 Operational Evaluation Conditions

Assessment of the rotorwash operational impact is performed by a set of evaluation cases. These cases are represented as scenarios. In each scenario, the rotorwash interacts with the external environment including personnel, terrain, structures, and equipment. The operational cases and associated scenarios were constructed to support JHL CDA but can be applied to future acquisition efforts.

In each scenario, a set of conditions defines the aircraft's rotorwash interaction with the external environment. Each interaction contains qualities and characteristics that affect the resultant size of the outwash footprint. Scenarios describe the interaction to link physical limits for personnel or objects in the ground environment to analytical prediction of wind velocity profiles generated within the rotorwash flow field. Nine scenarios were derived to represent the evaluation conditions. During the JHL CDA, these scenarios were refined with warfighter experience and expected future concept capability needs. The rotorwash evaluation scenarios are:

1. Ground Taxi
2. Hovering Taxi
3. Landing Zone Operations with Internal Payload
4. Landing Zone Operations with External Payload
5. Shipboard Operations with Internal Payload
6. Shipboard Operations with External Payload
7. Low Altitude Fly-Over
8. Airborne Operations – Hover
9. Airborne Operations – Low Speed

Each scenario contains a description of the operational task, flight state of the aircraft, environmental conditions, and the location of personnel. The expected contribution of the results to the overall operational rotorwash footprint is also defined.

A component of each scenario defines an operational task that is affected by rotorwash. This operational task definition is further expanded to identify the primary operational concern that requires the scenario to be evaluated.

The flight state of the aircraft encompasses the weight and operational characteristics that produce the highest flow velocity (including periodic effects) in the rotorwash region for an evaluation case. By using the maximum flow conditions in the analyses, these scenarios represent the corner points in the evaluation space for rotorwash interactions with the outside environment. This allows a limited number of total cases while capturing the impact to the warfighter.

Scenario environmental conditions describe the ground state under the aircraft. Ground conditions can vary significantly from an unprepared site with sand, rocks and/or dirt to the partial ground-plane of a shipboard deck with metal plating and deck movement. Other factors that will influence personnel limits, such as the variation in surface roughness that affects the mobility of ground personnel in dry and wet conditions, must also be identified.

The location of personnel within each evaluation case documents the presence of ground personnel in the vicinity of the aircraft. For some cases, such as taxi operations, ground personnel are not required in close proximity to the aircraft. The associated outwash footprint becomes a safe clearance area around the aircraft in this scenario. For external payload operations, the ground crew will need to be able to operate directly under the aircraft with the ability to safely enter/exit the hookup area. During this time the external load rests on the ground and does not contribute to the lift required by the rotor(s).

The potential operational impact section describes the operational activities that may be affected by the rotorwash. This provides rationale behind the scenario case and may influence or enable potential workarounds or mitigation for future platforms.

2.2 Description of Representative Rotorcraft

For purposes of predicting the rotorwash flow field, a rotorcraft can be modeled by its geometry, engineering parameters, and flight state. During conceptual level modeling, the rotorcraft can be characterized by simple geometry as depicted by the dimensions labeled in Figure 2-1 for a notional tiltrotor. High fidelity modeling requires more detailed rotorcraft geometry. Once the rotorcraft geometry is defined, the flight state is defined for each of the evaluation cases defined in Section 2.1. In conceptual level modeling, simple engineering parameters are used to generate the rotorwash predictions and link the geometry with the flight state. Although the present modeling development and representation is focused toward single main rotor helicopters, tandem helicopters, and tiltrotors, the methodology can be extended to other configurations. Engineering judgment should be applied for conceptual level modeling extrapolated outside of correlating data.

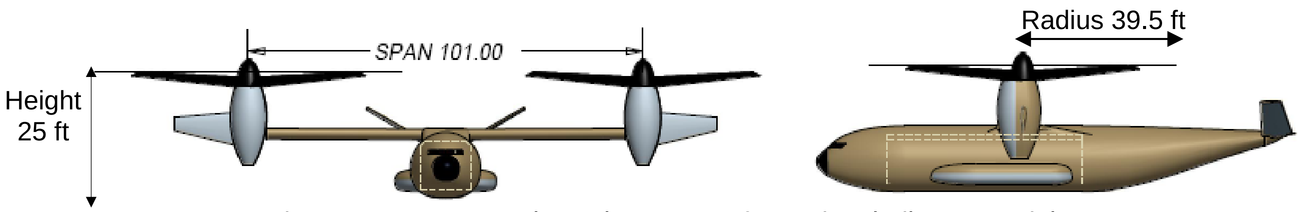


Figure 2-1 Conceptual Level Geometry for Notional Tiltrotor Model

3. OPERATIONAL ENVIRONMENTAL CHARACTERIZATION

The goal of this section is to define the primary hazards that predominate in the rotorwash environment and quantify threshold values that should not be exceeded for safety or economic related reasons. A summary list of these hazards, as determined from previous research is presented in Table 3-1. Each threshold value is referenced to a “peak” or “mean” condition. The peak condition relates to the highest velocity or force generated by wind gusts. The mean conditions relate to the average wind encountered. These recommended thresholds[2] are based on available data at this point in time. Should additional information or research become available, these recommendations should be updated.

3.1 Personnel Related Hazards

Personnel related hazards in the rotorwash environment can be classified into one of two main categories. The first category involves human performance limitations while functioning within the rotorwash velocity flow field. For example: “Are the wind forces so great that personnel will be blown over?” The second category involves physical injury as the result of being struck by a projectile or piece of flying debris that is blown by the rotorwash flow field.

3.1.1 Personnel Overturning Forces and Moments

The personnel overturning force and moment hazard applies to ground personnel in close proximity to rotorcraft. This hazard can be subdivided into military and civilian related limits. Differences between these categories arise from assumptions on the physical condition and training associated with military personnel functioning in the rotorwash environment. Civilians in close proximity to rotorcraft will have larger differences in age, physical condition, and experience background that require more conservative limitations on acceptable levels of rotorwash velocity.

3.1.1.1 Military Related Requirements

The estimation of forces and moments needed to destabilize and overturn military personnel has evolved over time as the result of several ground and flight test experiments. Two major tests with results from three references established personnel limits with respect to overturning forces and moments associated with the CH-53E [26]. A re-examination of these limits [5] and an extension of the original experiment to a larger sample size was conducted.

Personnel			
Overturning Force and Moment			
Military [4,5]			
Caution Zone	Mean	>80 lb force (wrt PAXman Model)	
Caution Zone	Peak	87-115 lb force (wrt PAXman Model)	
Hazard Zone	Mean	>87 lb force (wrt PAXman Model)	
Hazard Zone	Peak	≥115 lb force (wrt PAXman Model)	
Civilian (general population) [6,7]			
Caution Zone	Peak	33.6-44.7* mph wind velocity	$q = 2.88 – 5.12\ lb/ft^2$
Hazard Zone	Peak	> 44.7* mph wind velocity	$q > 5.12\ lb/ft^2$
Biophysical Injury			
Unprotected (eye) [8,9]		102 ft-lb/ft^2 particle energy /area	
Protected (incapacitate) [10]		58 ft-lb particle energy	
Structures			
Permanent Structures			
Wind Loading [11]	Mean	62.5* mph wind velocity	$q = 10.0\ lb/ft^2$
Asphalt Shingles [12,13]	Peak	60* mph wind velocity	$q = 9.21\ lb/ft^2$
Military Shelters [14]	Mean	55* mph wind velocity	$q = 7.74\ lb/ft^2$
Military Shelters [14]	Peak	65* mph wind velocity	$q = 10.81\ lb/ft^2$
Light Structures / Civilian Tents [1]	Peak	35* mph wind velocity	$q = 3.13\ lb/ft^2$
Materials Damage by Gravel**			
Glass (annealed glass) [15-20]		17 mph particle velocity	
Sheet Metal Damage (military) [21]		47.2 mph particle velocity for 0.02 inch depth dent	
Airport/Heliport Environment [1,22,23,24]	Peak	40.3* mph wind velocity	$q = 4.15\ lb/ft^2$
Landscaping [25]	Peak	39* mph wind velocity	$q = 3.89\ lb/ft^2$
*Wind Velocity Based on Sea Level Standard Atmospheric Conditions. Dynamic pressure (q = 0.5 * Air Density * Wind Velocity^2) should be utilized to determine appropriate wind velocity limit at other atmospheric conditions. **Representative gravel is ¾ inch with weight of 0.012125 lb (5.5 grams)			

Table 3-1 "Not-To-Exceed Threshold" Outwash Related Hazards

during JHL CDA [5]. The specific limits, as taken directly [4], are:

1. The Caution zone begins when peak wind force as calculated using the PAXman human body representation equals 87 lb. The Caution zone continues until the wind force equals 115 lb – moving to a hazard zone -- or when peak force drops back below 87 lb.

2. The Hazard zone begins when peak wind force as calculated using the PAXman human body representation equals 115 lb. The Hazard zone continues until the peak force drops back below 115 lb.

3. Although unlikely, in any case where the average force exceeds 80 lb regardless of peak force, there shall be a caution zone designation.

4. Although unlikely, in any case where the average force exceeds 87 lb regardless of peak force, there shall be a Hazard zone.

5. Two hazard/caution zone maps are required, one for zero ambient wind condition, and one for 20 knot headwind ambient wind condition.

In order for ground crew operations to be safe, the non-hazardous zone must be wide enough in order for the crew to have a path of safe entry into the downwash and under the aircraft. A rule of thumb would require at least a 45 degree entrance/exit path (vertex of the angle located at the center of the aircraft downwash pattern).

The PAXman model was developed for military personnel as a reference area for wind drag calculations. It is based on the projection of a 6-foot tall person crouched over and leaning, as he would appear while immersed in the outwash. The detailed geometry of the PAXman model and the analysis methodology [27] are used to calculate drag. Figure 3-1 and Table 3-2 are taken directly from the reference [27] and document the PAXman area distribution as a 9th order polynomial (half of body width).

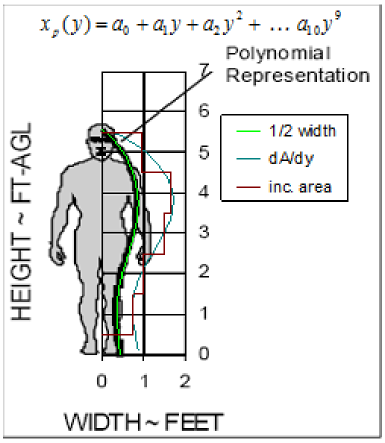


Figure 3-1 PAXman Area Distribution [27]

a0	4.30939E-01
a1	-4.63972E-02
a2	-1.39649E-01
a3	1.37545E-01
a4	-2.48764E-02
a5	-5.49253E-04
a6	2.21653E-04
a7	-4.18444E-05
a8	1.45194E-05
a9	-7.80009E-08
a10	-1.89822E-07

Table 3-2 Polynomial Coefficients [27]

3.1.1.2 Civilian Related Requirements

Civilian related requirements for wind exposure and overturning force are distinctly different than those for military personnel. Factors such as weight, size, age, health, protective clothing, and task (i.e. holding umbrella or pushing stroller) all have important effects on wind velocity threshold limits. The wind engineering community has studied this subject for numerous reasons over the last 40 years. No references were identified that connect any of this research directly to rotorwash applications. However, for civilian rotorwash scenarios, this research provides excellent background and guideline information. The outwash peak velocity approximates the gusty wind conditions for the derived limits. Based on the information collected for personnel rotorwash hazards from a variety of sources, the equivalent “Caution Zone” is 33.6 – 44.7 mph and the “Hazard Zone” is any peak velocity > 44.7 mph at sea level standard conditions. At other atmospheric conditions the resultant dynamic pressure should be utilized to derive the appropriate velocity limits.

3.1.2 Personnel Biophysical Injury

Personnel “biophysical injury” in the context of this paper is defined as “any injury that is the result of being struck by a projectile or debris that is propelled through the air by the rotorwash flow field”. Two major areas of concern have been identified: “What projectile velocities are required to penetrate or severely bruise human skin?”, and “What projectile velocities are required to damage the unprotected human eye?” For unprotected personnel, the limiting factor is damage to the eye. The limiting factor for protected personnel is impact by airborne debris. Protective equipment includes eye, skin, and hearing protection. Clothing insulation may also be required for heat loss (i.e. wind chill).

Small objects propelled by rotorwash will produce progressive amounts of eye damage from corneal abrasion, hyphema (bruising), lens dislocation, retinal detachment, and globe (eyeball) rupture. Eye damage criteria apply to both unprotected civilian and military personnel. For this hazard, a conservative limit of 50% risk of corneal abrasion equates to 102 ft-lb/ft^2 as the limiting factor according to the reference information [8,9], where ft-lb/ft^2 is object kinetic energy divided by its area of surface at impact.

Larger objects propelled by rotorwash can penetrate or severely bruise human skin. All velocities associated with these projectiles are related to their kinetic energy and not the rotorwash wind speed that generates the flying debris. Using documentation provided [8], protected personnel are estimated to have a limit of 58 ft-lb of impact energy before becoming incapacitated due to impact by an airborne object or piece of debris.

3.2 Ground Structure Related Hazards

The wind velocities generated by a rotorwash flow field can damage or collapse structures. Three major categories of structures are considered: permanent structures, military shelters and tents, and light structures / civilian tents. Each category has different limitations as a function of wind speed at sea level standard conditions. At other atmospheric conditions the resultant dynamic pressure should be utilized to derive the appropriate velocity limits.

3.2.1 Permanent Structures

Building codes in the United States (and most developed countries) have extensive wind loading requirements for single- and multi-story buildings, signs, and almost all other types of permanent structures. A separate limiting factor for building damage is the wind speed that, when exceeded, can result in damage to asphalt shingles. These two measures become the defining metrics for rotorwash damage to permanent structures and were derived from the referenced dataset [1,11,12,13,14]. These not-to-exceed metrics are 62.5 mph mean velocity for wind loading and 60 mph peak velocity for asphalt shingles.

3.2.2 Wind Loading on Military Shelters and Tents

Military shelters and tents are frequently cited in the literature and mishap databases as being involved in rotorwash mishaps. From a literature survey, the wind limits ranged from 40 mph to 100 mph. Based on the type and prevalence of types of structures, the researchers chose a 55 mph mean velocity limit and a 65 mph peak velocity limit for association with this category [14].

3.2.3 Wind Loading on Light Structures and Civilian Tents

For the purpose of this paper, light construction is considered to be non-permitted, loosely constructed shelters. These shelters are ill defined and are considered to have wind resistance characteristics similar to civilian tents. From the a literature survey, the peak wind velocity is 35 mph[1]. This wind velocity is equated to the peak velocity in the outwash flow field.

3.3 Hazards Involving Impact Damage and Materials

Rotorwash related hazards involving debris and material impact often involve complex scenarios. For example, a rock, ejected by the rotorwash flow field, could shatter plate glass or break a vehicle windshield. The broken glass might also then become an airborne hazard to personnel. This section focuses on limitations associated with the initial impact of the material from rotorwash transported debris. These not-to-exceed limits are associated with several generally accepted damage concepts that are further associated with glass, metals, and composites - irrespective of how the debris impacts the material. A ¾ inch piece of gravel with mass of 5.5 grams (0.012125 lb) was chosen as the representative particle to measure impact from airborne debris.

3.3.1 Glass

Four main types of glass were focused on: 1) annealed (or “ordinary” glass), 2) heat-strengthened, 3) tempered, and 4) laminated glass. Most glass products are made from annealed glass, which is often referred to as “ordinary” glass. Different applications use different types of glass. A conservative not-to-exceed limit uses the lower part of a specified mean minimum breakage velocity (MMBV) range. This range is based on glass type, glass thickness, and standardized projectile or debris mass/energy/velocity combinations that could be present in windstorms or rotorwash flow fields. Using information derived from references [15-18], annealed glass from 0.2-0.4 inch thickness can withstand projectiles up to 5.5 grams with a MMBV of 17 mph or less (projectile velocity, not wind velocity). This represents the limit associated with glass used for general purposes.

3.3.2 Sheet Metal

In general, small particles or projectiles require substantially less energy to dent steel or aluminum sheet metal than to penetrate it. Components with sheet metal outer construction are frequently associated with other aircraft or vehicles. Debris damage to material coating (scratching of paint) is not considered as a limiting factor. Sheet metal material damage in civil applications is not expected to be a limiting condition for rotorwash environmental limitations due to the lower limit expressed in 3.3.1. For military aircraft operating in proximity to each other at unimproved landing sites, material damage limit(s) would facilitate determination of separation between aircraft. Using existing automotive research, a 0.02-inch depth dent was arbitrarily chosen by the authors as a limiting condition. Assuming kinetic energy equivalency with the automotive test, a ¾ inch piece of gravel would have a velocity limit of 47.2 mph to produce the 0.02-inch dent [21].

3.3.3 Composite Panels

Properties of composites vary greatly with their application. In general, composites tend to be stiffer, less elastic in deformation, and have different properties from metals that define damage tolerance. While damage to composite panels may occur from debris carried in the flow field, composite material damage is not expected to be a limiting condition for rotorwash environmental limitations for civilian applications due to the lower limit expressed in 3.3.1. For military applications, further research or application of existing research should be applied to determine acceptable damage levels and velocity limits associated with the representative ¾ inch gravel.

3.4 Airport/Heliport Environment

Research into the airport / heliport environment has not yielded significant quantifiable data, i.e. wind speeds, which can be used for detailed hazard analysis purposes. However, the available data has provided some insight as to recommended thresholds that should not be exceeded. These insights, derived from references [1,22,23,24], are based on literature derived data based on various types of rotorwash related incidents, helicopter wind limitations, and lessons learned. Based on review of these references, any rotorwash peak profile velocity above 40.3 mph has the potential to result in an airport/heliport incident of some type at sea level standard conditions. At other atmospheric conditions the resultant dynamic pressure should be utilized to derive the appropriate velocity limits.

3.5 Landscaping

Rotorwash has been documented to damage surrounding plants and trees in numerous scenarios. However, a review of published rotorcraft related literature does not indicate any recommended velocity limits to avoid this damage. In contrast, research on windstorm damage does provide significant insight into the wind gust magnitudes that can damage plants and trees. The proposed rotorwash plant and tree limit (landscaping size) in the civil environment is 39 mph peak velocity at sea level standard conditions. This wind speed corresponds to the lower bound of Beaufort Number "8" where tree and plant damage begins [25]. At other atmospheric conditions, the equivalent dynamic pressure should be utilized to derive the appropriate velocity limit.

4. ROTORWASH MODELING METHODOLOGIES

Rotorwash modeling methods, like most aerodynamics models, vary from simple conceptual models to highly complex computational fluid dynamics models. The rotorwash design goal of this project requires a model with rapid computational turnaround time that can be quickly adjusted for rotorcraft configuration differences, i.e. single main rotor, tandem, and tiltrotor configurations. These requirements inherently lead to the development of a simple modeling approach. The momentum-based modeling approach was chosen to achieve these goals.

4.1 Reference Test Data

4.1.1 Flight Test Data

Flight test data of varying quality is available for calibration of both the conceptual level momentum based modeling and high-fidelity modeling. Based on the available data, the models were primarily correlated to CH-53E [26], V-22 [28], and CH-47 [27] flight test data. These three sources represent the highest quality data for a range of flight conditions. Correlation of the conceptual level model was also conducted to lower quality flight test data for the XV-15 [29] and H-60 [30]. Full-scale outwash data is often unrepeatable and subject to the variances inherent to flight testing.

4.1.2 High-Fidelity Tool Modeling Data

Current high-quality flight test data are limited in the range of disk loading, hover height, and location of velocity measurement sensors. It is hoped that these data sets can be extended with some confidence by calibrating a high fidelity tool's (computationally expensive) methodology to generate an expanded range of data outside of the flight test data set. This extended data set should then be utilized to correlate a conceptual level model with increased confidence when extrapolating beyond the range of measured flight test conditions. However, at present the very complex and unsteady flowfield of a rotorcraft in-ground-effect has only recently begun yielding to physics-based treatment. In absence of adequate analytical tools, full-scale flowfield surveys remain the most viable means of characterizing the outwash flow field.

4.2 Rotorwash Conceptual Level Momentum-Based Model

The momentum-based rotorwash model, RoWFoot, contains elements from previous efforts of the authors and others. The best components of these previous efforts are consolidated and extended using computer tools and high quality flight test data that did not exist at the time that the previous versions of the models were developed.

Correlation of the conceptual level model was conducted for the CH-53E, V-22, CH-47, XV-15, and H-60. From this correlation effort, effects of gross weight, rotor disk loading, ground effect, the number and position of the rotors, and the outwash distance from the center of the rotorcraft were evaluated for the conceptual model. An example of the conceptual model correlation appears as Figure 4-1. Test data points in the mean velocity profile are the average wind velocity over the time interval that data were taken. In the peak velocity profile, the data points are the highest magnitude recorded for each sensor over the time interval.

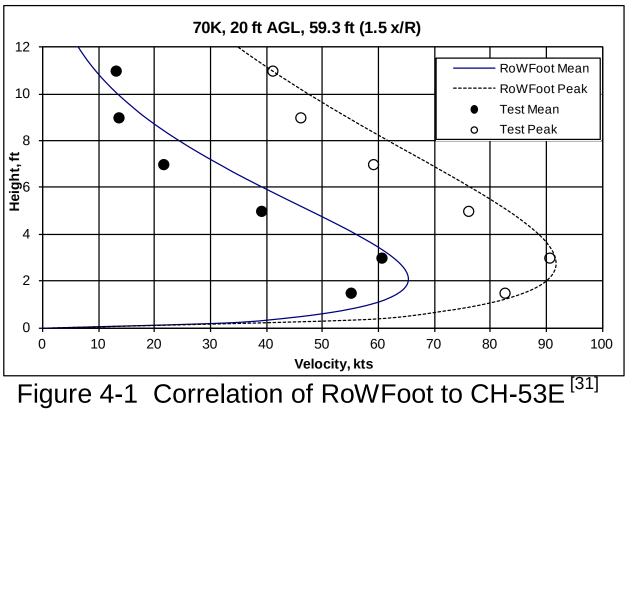


Figure 4-1 Correlation of RoWFoot to CH-53E [31]

4.3 Rotorwash High Fidelity Modeling

An attempt at high fidelity modeling was conducted using the CHARM vortex model [32] to reproduce the land-based V-22 rotorwash downwash survey [28]. In this correlation effort, effects of gross weight, rotor disk loading, ground effect, the number and position of the rotors, and the outwash distance from the center of the rotorcraft were evaluated for use in conjunction with the conceptual model.

Review of the model correlation identified discrepancies with the CHARM modeling symmetry, gross weight to maximum velocity trend, and height above ground to maximum outwash velocity trends that indicate the modeling results are of limited utility in extension of the rotorwash flight test database.

Although these results are not usable to provide confidence of conceptual level model extrapolation beyond the region bounded by flight test data, the results and methodology were retained to display lessons learned and facilitate further work in this effort.

4.4 Shipboard Effects on Rotorwash

Personnel near or underneath rotorcraft (i.e. sling load operations) during shipboard operations have a very limited area to work and ships typically launch/recover aircraft into the wind. Also, the effect of a rotor being partially over the deck edge (i.e. the V-22) has significant effects on the development of the rotorwash flow field below the aircraft when compared to operation over land. Development or refinement of the associated conceptual level model is hampered by the lack of test data.

4.4.1 Effect of Wind-Over-Deck (WOD)

V-22 test data that document rotorwash effects from the wind-over deck shipboard environment or the ambient wind at a land location are very limited in quantity. However, these data provide a limited understanding of what can be expected for a typical tiltrotor WOD launch condition. The peak upwind profile velocities were substantially less at 0 and 20 knot WOD conditions when compared to the 0 knot condition on land (note 4.2.2 below). The peak downwind profile velocities averaged 10 knots more at the 20 knot WOD condition when compared to both the land and shipboard 0 knot conditions. This evidence agrees with operational experience with shipboard operations.

4.4.2 Effect of shipboard deck edges

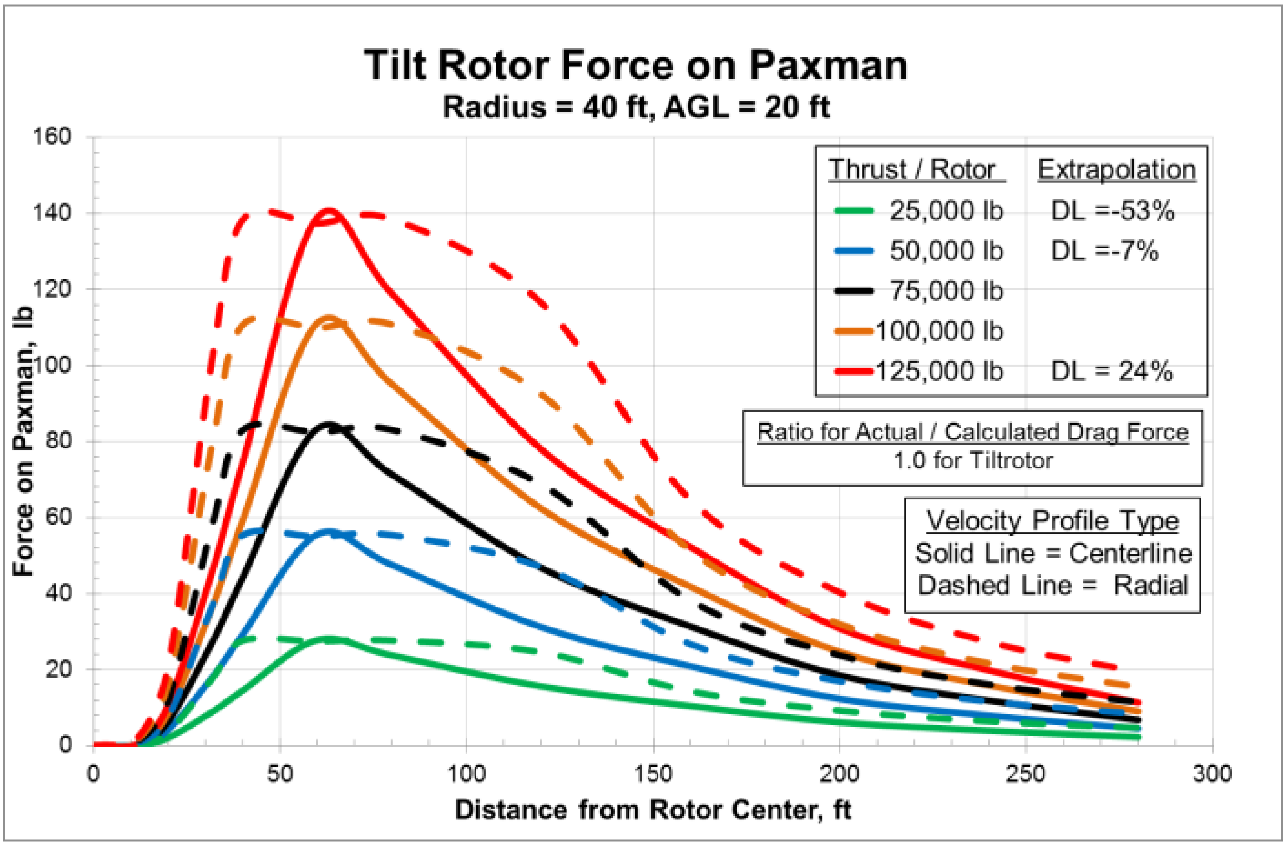
When a hovering rotorcraft has a portion of one of its rotors over the deck edge, the rotorwash flow field will be affected due to associated loss of mass flow “dumped” overboard and not appearing on the flight deck. Limited test data indicate the rotorwash flow field for the V-22 resembles those of single rotor helicopter velocity profiles on land when one of the rotors is exposed ~50% over the edge of the flight deck.

4.5 Personnel Stability Limit Ratio

The drag force on personnel is determined using the wind speed and shape of the representative person. For modeling purposes, a standard “PAXman” net frontal area distribution is used to represent the outline of a person in the outwash. Personnel maximum drag force uses this area with the peak velocity profile. As noted in Section 4.2, the peak velocity profile is a “worst case” compilation of maximum recorded wind speed magnitudes over a time interval and thus may over predict the associated peak drag force. To account for this over prediction and the effect of the non-steady rotorwash flow, the peak predicted drag force is connected to the personnel capability limits in Section 3.1.1.1 with a personnel stability limit ratio of 0.8 for helicopter and tandem configurations and 1.0 for tiltrotors. This ratio is the actual peak drag force on personnel divided by the predicted peak drag force on personnel based on an analysis of test data [1,27,28,31].

4.6 Conceptual Model Trends

At equivalent rotor conditions, outwash wind velocity profiles are dependent on the type of rotorcraft configuration. The separation distance of multiple rotors changes the magnitude and distribution of the mass flow. For the radial outwash, at the same thrust per rotor, the helicopter, tandem, and tiltrotor have similar mean velocity profiles. Within the peak velocity profile, the helicopter and tandem velocity profiles are similar, while the tiltrotor’s is smaller in magnitude. For centerline outwash, the tandem velocity magnitude (lateral axis) is higher than the tiltrotor (longitudinal axis). These differences are supported by flight test data. Explanation of the differences arises from the distribution of the air mass flow within the rotorwash. As an example, Figure 4-2 describes the RoWFoot model sensitivity of a tiltrotor to changes in thrust/rotor and height above ground to force on PAXman. Flight conditions that are extrapolated outside the bounds of test data for disk loading or rotor height above ground are indicated in the legend along with the magnitude of the exceedance.



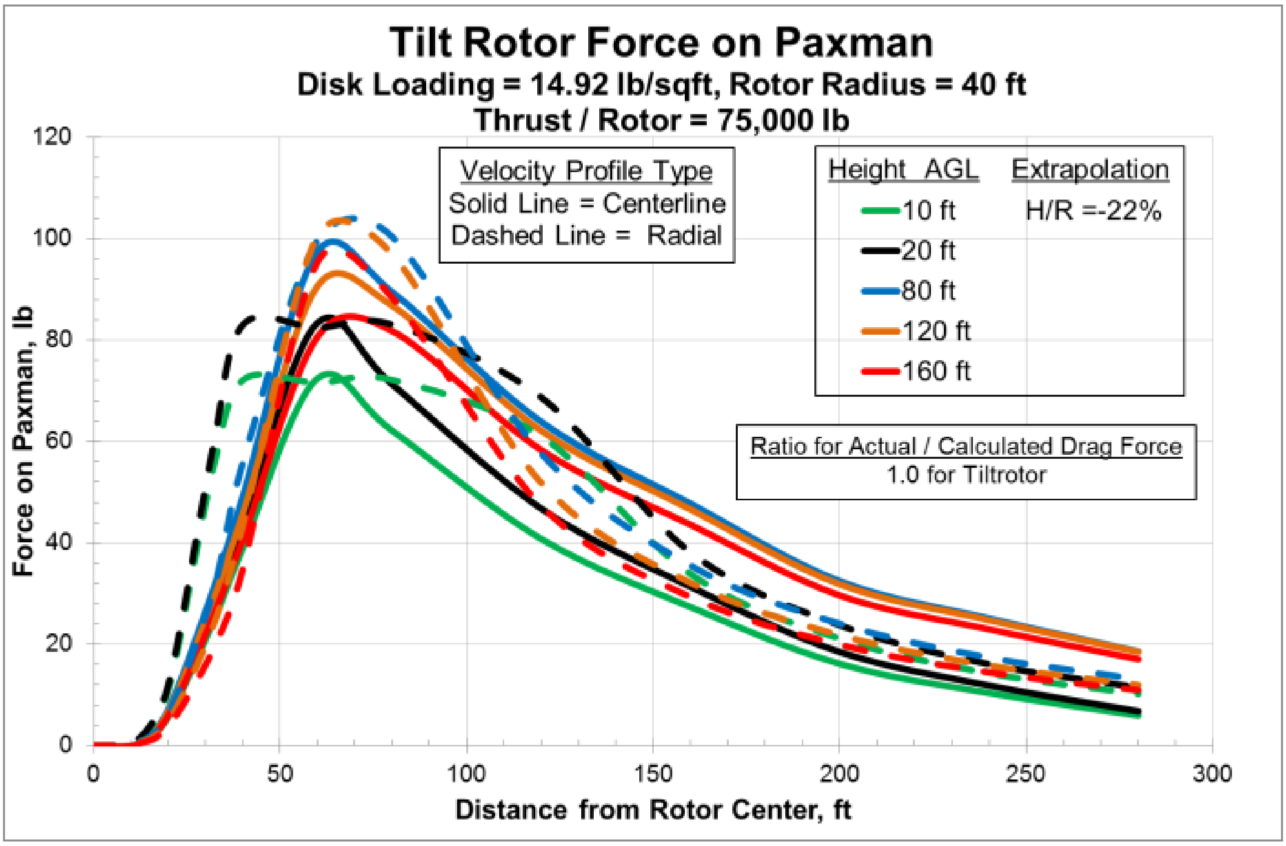


Figure 4-2 Tiltrotor Operational Parameter Trends for Force on PAXman

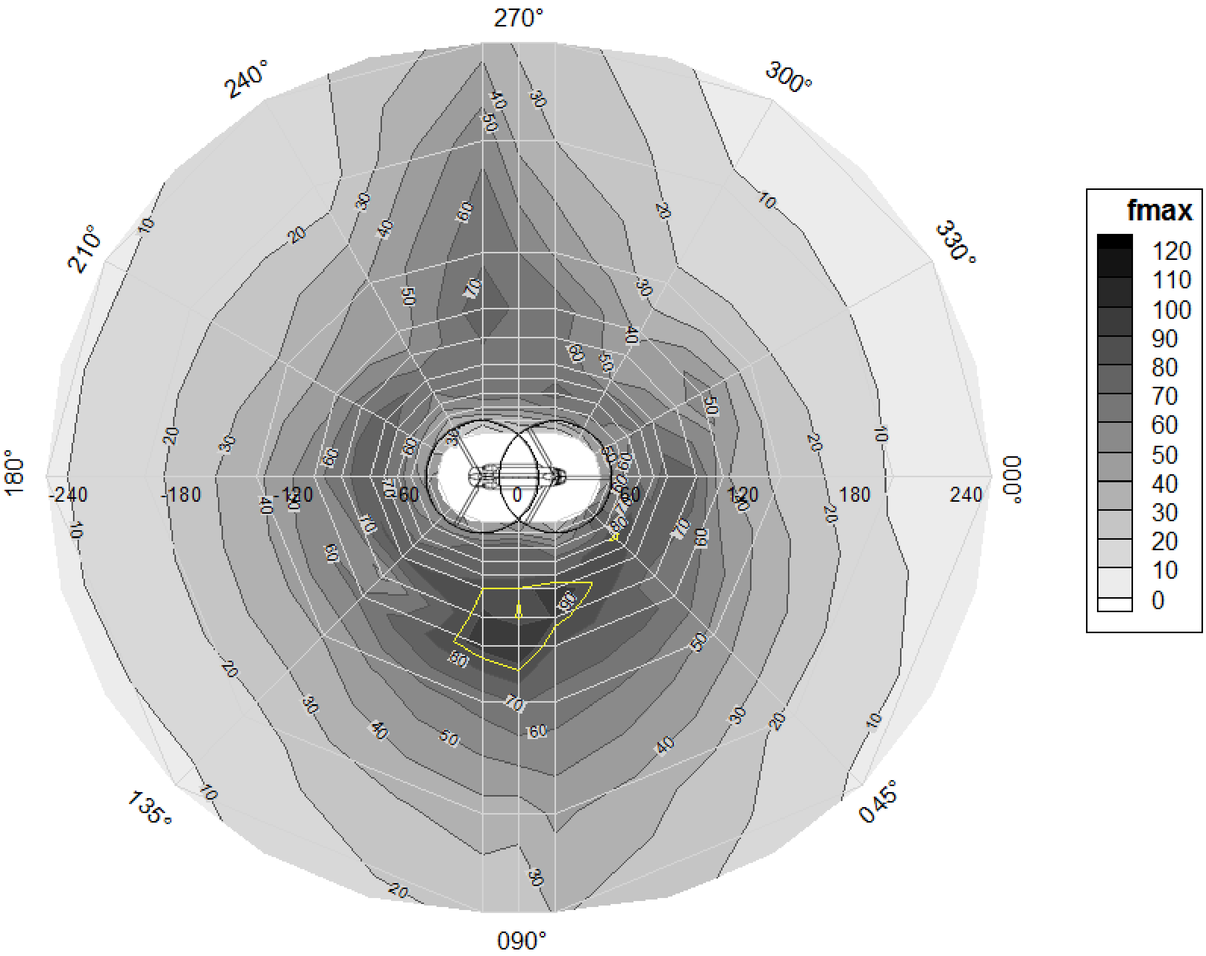


Figure 5-1 Outwash Survey Peak Forces Determined from Experimentally Testing a CH-47 at a 20 ft AGL Hover at 41,000 lb [27]

5. FOOTPRINT OF LARGE ROTORCRAFT ON OPERATIONAL ENVIRONMENT

Rotorwash footprints display the operational impact of the outwash around a hovering rotorcraft. These footprints are generated for the evaluation assessment conditions of section 2.1. Contours within these footprints represent the constant values of velocity or force within the operational environment. The contours arise from post-processing of the rotorwash analytical modeling (Section 4) output at defined evaluation conditions. Environmental limits were previously defined in Section 3. The rotorwash analytical modeling is the RoWFoot tool as briefly described in section 4.2. This type of representation provides a visual display of the rotorwash impact on the ground environment.

Figure 5-1 presents an example CH-47 outwash personnel force footprint using experimentally measured velocity profile data. This technique is identical to the process used with RoWFoot generated velocity profile data in lieu of experiment data for creation of operational footprints.

As introduced in Section 2.1, there are nine evaluation scenarios. Rotorwash footprints can be generated for the first six of the nine scenarios using the notional tiltrotor described in Section 2.2 (the last three scenarios are not presently capable of being modeled). Rotorwash footprints can be produced using the outwash wind velocities or forces of the first six evaluation scenarios. The remaining three scenarios are evaluated via similarity to field experience with DoD rotorcraft.

Footprints for the six evaluation scenarios represent the typical operational conditions of the rotorwash impact on the ground environment. The full set of conditions for the evaluation space is summarized in Table 5-1. Utilization of the evaluation space conditions highlights areas of concern to the warfighter at historical operational conditions. Based on this information, the user can then apply mitigation techniques as needed to lower the rotorwash impact to acceptable conditions. Section 5.1 contains an example of the notional tiltrotor for the third assessment scenario – “Landing Zone Operations with Internal Payload”.

Operational Evaluation Scenario	Gross Weight lb	Hover Height ft	Thrust to Weight Ratio	Altitude & Temp ft / deg F
Ground Taxi	30% Maximum GTOW	0	0.30	0 / 59
Hovering Taxi	Maximum GTOW	10	1.09	0 / 59
LZ Operations, Internal Payload	Maximum GTOW	20	1.09	0 / 59
LZ Operations, External Payload	Maximum GTOW – External Load	50	1.09	0 / 59
Shipboard, Internal Payload	Maximum GTOW	20	1.09	0 / 59
Shipboard, External Payload	Maximum GTOW – External Load	50	1.09	0 / 59

Table 5-1 Rotorwash Operational Evaluation Space Conditions

The operational footprint includes a scenario explanation, operational conditions, graphic representation of the rotorwash footprint for velocity and force, and mitigation sources. The graphic representation of the example rotorwash operational footprint for the LZ Operations, Internal Payload evaluation case is presented as Figures 5-2 and 5-3.

For the notional tiltrotor, the aircraft weight is based on the Maximum Gross Take-Off Weight (GTOW) of 141,605 lb. This corresponds to a disk loading of 15.7 lb/ft^2, where the disk loading is in terms of thrust. During external load operations, the aircraft weight does not include the external load (indicating the load has not been picked up). The external load is assumed to be a MILVAN plus external load handling kit (45,275 lb = 44,800 lb + 475 lb). External load operations use an aircraft weight of 96,330 lb which corresponds to a disk loading of 10.7 lb/ft^2. For each operational evaluation scenario there is an associated velocity and force footprint. Hover heights are representative of typical heights above ground of the landing gear based on historical operations. As seen in Figure 4-2, changes to the hover height affect the outwash conditions in the ground environment. For the notional tiltrotor, the distance from the landing gear to the rotor is 25 feet.

Thrust-to-weight ratio is the amount of thrust produced by the rotor relative to the aircraft gross weight. The delta above unity is due to vertical drag, or download, produced by the rotor induced flow over the airframe. During flight, the download is assumed to be 9% for the notional tiltrotor.

The altitude and temperature will vary based on mission requirements. As the altitude and temperature increases, the aircraft may not have the capability to hover at its Maximum GTOW. For the scenario conditions shown in Table 5-1 and Figures 5-2 and 5-3, the altitude and temperature were fixed at sea level standard values to enable flight at the Maximum GTOW.

Velocity footprints display the highest magnitude values in the outwash peak velocity profile. Force footprints display the peak force on ground personnel using the PAXman model. Both the velocity and force footprints can be associated with data previously presented in Table 3-1 as operational limits. Table 5-2 contains the limits associated with the peak velocity and Table 5-3 contains the limits associated with drag force on military personnel. These tables are referenced with the Rotorwash Velocity and Force Footprints in Figures 5-2 and 5-3 for the example case.

Environmental conditions may lower the values expressed in Tables 5-2 and 5-3. In Table 5-2, civilian wind limits may be lower if combined with uneven terrain, slick surfaces, and/or poor visibility. Table 5-3 force limits will be reduced for uneven terrain, slick surfaces, and/or poor visibility as well as rolling ship decks. Slick surfaces include wet grass, mud, and wet ship decks. Poor visibility can occur from blowing water spray, rain, sand, snow, dust, and other airborne particles. Laboratory tests that quantified the civil and military personnel wind and force limits were collected while test subjects had good footing and visibility.

Hazard Consideration	Dyn Press (lb/ft^2)	Wind Speed (mph)
Civilian (General)		
Caution Zone	2.88-5.12	33.6-44.7
Hazard Zone	> 5.12	44.7
Asphalt Shingles	9.21	60
Military Structures	10.81	65
Light Struct. / Civilian Tents	3.13	35
Airport / Heliport Environment	4.15	40.3

Table 5-2 Wind Velocity Limits for Ground Environment

Force, lb			
Caution Zone	>80 (mean)	OR	87–115 (peak)
Hazard Zone	>87 (mean)	OR	≥ 115 (peak)

Table 5-3 Force Limits for Military Ground Personnel

5.1 Operational Footprint Example - Landing Zone Operations with Internal Payload

This scenario simulates hover over an unprepared or austere landing zone at a hover wheel height of 20 ft. The primary concern is the clearance area associated with personnel, equipment, and other aircraft in the ground environment. The rotorcraft is assumed holding a constant altitude at maximum take-off gross weight where the rotorwash flow field is stable. During this maneuver, the download on the airframe is 9% and is represented with a thrust / weight ratio of 1.09. Table 5-4 summarizes this scenario's operational conditions.

Using these operational conditions, the rotorwash operational footprint for velocity is presented in Figure 5-2 and force on personnel is presented in Figure 5-3. Using the wind limits in Table 5-2 and the force limits in Table 5-3, safe separation distances can be identified for personnel, equipment, and structures in the ground environment.

Gross Weight	141,605 lb (Maximum GTOW)
Thrust / Weight	1.09
Altitude / Temp	0 ft / 59 deg-F
Hover Height	20 ft AGL

Table 5-4 Landing Zone Operating with Internal Payload Conditions

This scenario does not require ground crew, equipment, or personnel to be in close proximity to the aircraft during the take-off and landing. Number and type of people located in the ground environment will be mission dependent and may include civilians and/or military personnel. Ground control personnel in the vicinity are expected to be trained and protected military personnel. Operational needs such as the physical dimension of the landing zone size may result in closer separation than desired to military ground personnel, civilians, equipment, and structures.

Some of the rotorwash effects may be operationally mitigated by removal of personnel or equipment in the ground environment, modifying the state of the limiting condition (i.e. sheltering, bracing, protecting, …), or changing the operational condition of the aircraft from Table 5-4. The operating condition may necessitate a lower aircraft weight or conducting a ground taxi to approach the desired location. Civilians located in the outwash flow field can be braced and shielded by protected military personnel to increase their allowable velocity limits. Ambient winds may be used to divert some of the rotorwash away from sensitive areas. The yaw angle of the tiltrotor (and tandem), can also be changed to orient the most benign outwash zone toward sensitive directions during take-off and landing.

The other five evaluation scenarios for 1) Ground Taxi, 2) Hovering Taxi, 4) LZ Operations, External Payload, 5) Shipboard, Internal Payload and 6) Shipboard, External Payload use a similar evaluation methodology and display of results.

5.2 Other Evaluation Conditions

Currently, the modeling is not capable of generating output footprints for the Low Altitude Fly-Over, Airborne Operations – Hover, and Airborne Operations – Low Speed conditions. These cases are evaluated as follows.

5.2.1. Low Altitude Fly-Over

Operational experience indicates that rotorwash from a low altitude fly-over with the rotorcraft in helicopter mode does not significantly impact the ground environment, as long as the aircraft is approximately five rotor diameters above the ground. For this scenario's flight speeds and altitudes, the outwash component of the rotorwash either does not have time to form or dissipates enough before reaching the ground, and thus the ground environment is not significantly affected.

5.2.2. Airborne Operations – Hover

Operational experience indicates that rotorwash from hovering does not significantly impact the ground environment as long as the aircraft is approximately five rotor diameters above the ground. For this scenario's altitude, the outwash component of the rotorwash dissipates enough before reaching the ground, and thus the ground environment is not significantly affected.

5.2.3. Airborne Operations – Low Speed

Operational experience indicates that rotorwash from airborne operations at low speeds does not significantly impact the ground environment, as long as the aircraft is approximately five rotor diameters above the ground, but that it could impact other aircraft in the immediate vicinity. At these altitudes, the outwash component of the rotorwash will dissipate before reaching the ground, and thus the ground environment is not significantly affected. If the concern is the rotorwash impact on other aircraft, safe separation distances must be maintained in both the horizontal and vertical planes, as defined in standard military practices for tiltrotor aircraft.

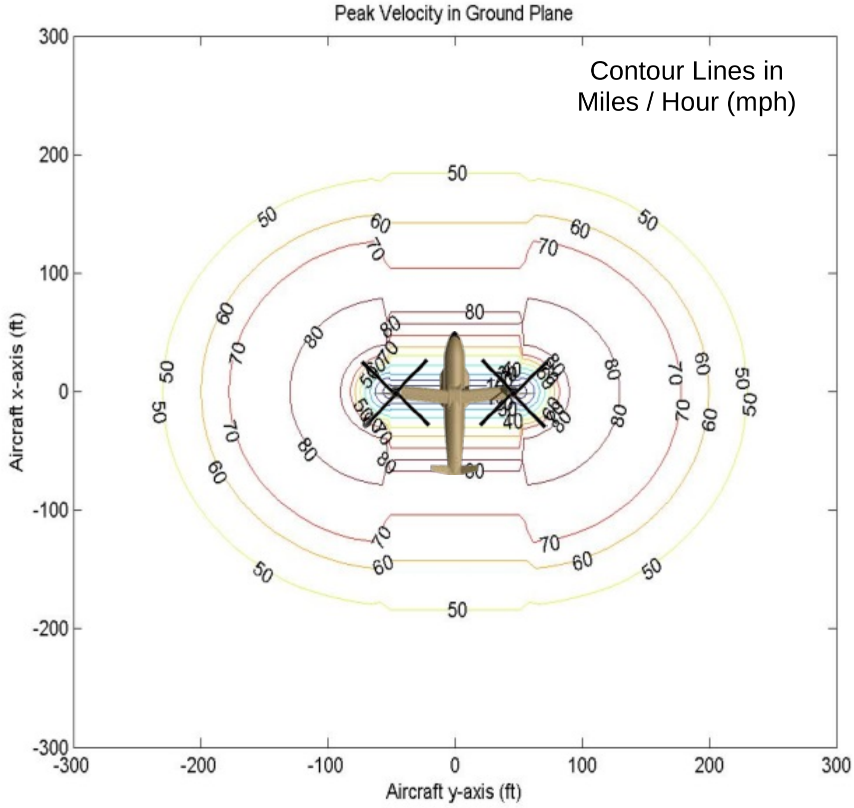


Figure 5-2 Peak Velocity Contour Plot

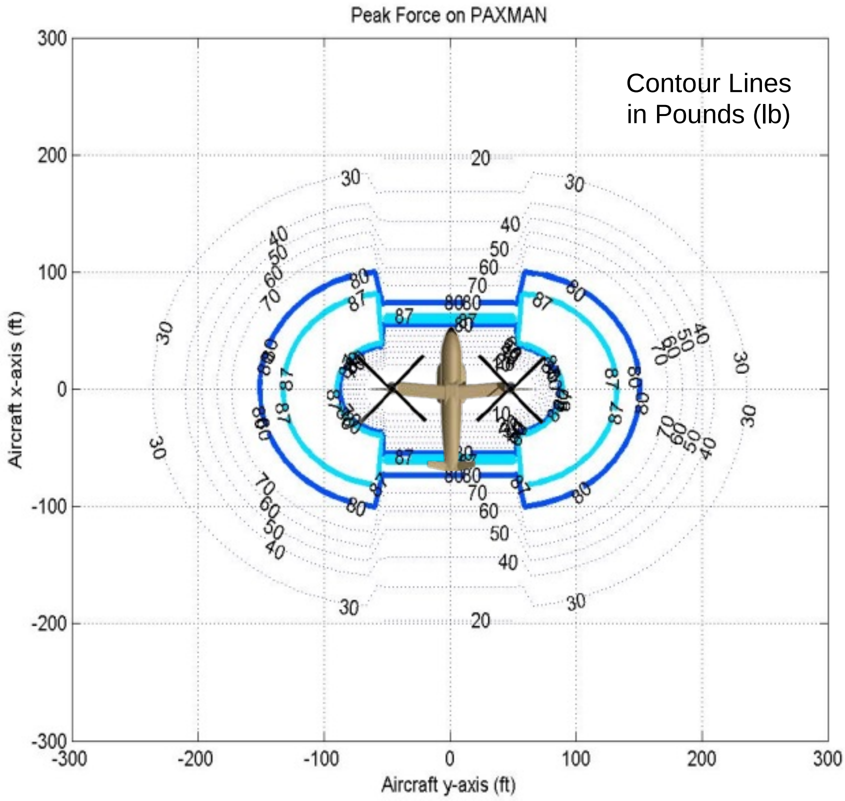


Figure 5-3 Personnel Force Contour Plot

6. CONCLUSIONS

This paper presents an approach to define the operational footprint produced by rotorwash on the surrounding environment. This approach incorporates processes, limits, modeling, and display to graphically depict the rotorwash operational footprint for current and future VTOL aircraft. This depiction allows "visualization" of the impact of the outwash on the surrounding environment and the recommended separation distances required for personnel, structures, equipment, other aircraft, and landscaping for safe operation.

The goals are to support development and evaluation of a rotorwash related performance specification with key specification elements, quantification of environmental limits, and development of the associated tools and analysis methodology.

The suggested specification for future military VTOL aircraft is as follows in italics:

Rotorwash shall permit operations up to operational capability limits without endangering, damaging, or exceeding physical capabilities of personnel, equipment, or structures. Specifically the rotorwash shall allow safe operation during:

- *Ground and air taxi maneuvers*
- *Operations from an unprepared landing zone with internal and external loads*
- *Shipboard operations with internal and external loads during air operations*
- *Airborne operations including hoist, fast rope, air-to-air refuel, and air drop*

Rotorwash footprints for unprotected military and civilian personnel, structures, equipment, airport / heliport environment, and landscaping are not considered to be driving requirements for a military performance specification. Resultant footprints for these considerations graphically display the safe separation distances from the VTOL aircraft.

The military and civil environmental limits are established as based on a combination of testing and literature review. These limits include wind limits for civilians, equipment, and structures; force limits for military personnel; energy limits for biophysical injuries; and velocity limits for materials damage.

The tools developed are capable of modeling rotorwash for a single main rotor, tandem, or tiltrotor configuration at the conceptual level. Empirically derived modeling can be refined or extended to a wider range of configurations and validity ranges with additional data.

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