

Establishing Fluid Dynamics Scales Critical to Dynamic Interface Applications and their Impact on Handling Qualities

FY 2024 Report

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Abstract

The goal of this effort is to develop a better understanding of the relationship between the length and time scales typically present in the disturbance fields experienced by Naval aviators (i.e. ship airwakes, wing wakes etc.) and rotorcraft flight dynamics and flying qualities when the fully-interacting fluid dynamics of the disturbance and rotor wake and flight mechanics are accounted for. With this information in hand, the engineering community would be better able to:

- Understand the relationship between aircraft type, ride quality, flight dynamics and handling qualities during flight conditions where disturbance fields are encountered.
- More accurately define trainer requirements, minimum experimental campaign requirements, minimum CFD modeling requirements and consequently establish a benchmark to evaluate CFD predictive capability.
- Better define the requirements for new aircraft given the direct correlation between flight dynamics and handling qualities.

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Summary

One of the most demanding tasks for naval aviators is landing on a moving flight deck in high sea-states (i.e. the dynamic interface (DI) problem - see Figure 1). This task is made even more difficult by aerodynamic disturbances at the landing spot from the flow around the ship's bow, superstructure and deck edges. This highly unsteady ship airwake can lead to significant pilot workload. Flight simulation has long been recognized as a valuable tool for augmenting engineering development and pilot training in DI operations, however, it is most effective when the underlying simulation model has appropriately characterized the complex aerodynamic interactions between the rotorcraft and ship airwake. Given the complexity of the problem, a fundamental difficulty when assessing the simulation approaches is the quantification of “good enough”, both from the standpoint of understanding and predicting the underlying physics and also with regards to trainer fidelity (i.e. can the pilot feel/tell a difference). The premise of the proposed effort is to quantify “good enough” with regards to understanding the fundamental aero-physics of a rotorcraft interacting with an external disturbance field to quantify which length and time scales - such as those present in a ship airwake or in the wake of a an upstream aircraft during formation flight/refueling - directly impact the aircraft's fundamental response and flying qualities (FQ)¹ along with the aeromechanics modeling fidelity required to simulate interactions adequately.

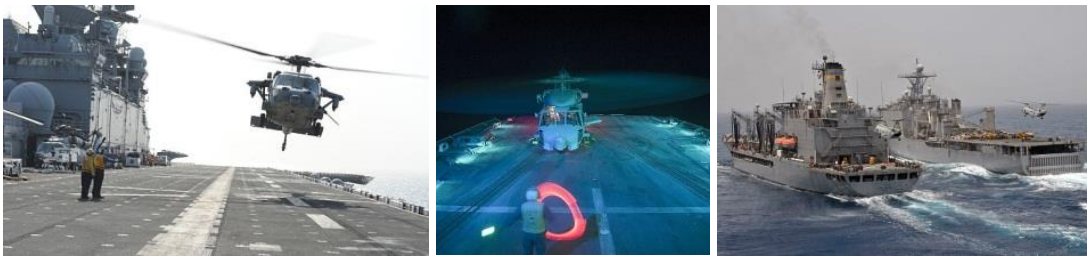


Figure 1: DI scenarios: landing on a moving deck (left), night operations (center) and approaching a pair ships (right)

Several ONR funded efforts that seek to quantify “good enough” have recently completed, or are underway, at the University of Maryland, Georgia Institute of Technology and NAVAIR, where the academic researchers are focusing on understanding the response of a wing to the wake shed by canonical structures [1] and the latter (Generalized Airwake Goodness Evaluation) program seeks to represent the entire DI scenario with a variety of methods. This effort does not seek to duplicate that work, rather to complement it by focusing on several fundamental unknowns in the rotorcraft community, namely:

1. What spatial and temporal scales, present in a disturbance field, matter from Flight Dynamics (FD) and FQ standpoints? Beyond the obvious constraints (i.e. larger than a

¹ It is worth noting that there is a trend in the community to generalize and over use the term “handling qualities”, and not be specific. David Key, one of the primary creators/instigators of ADS-33, liked to differentiate between flying qualities, and handling qualities. In his definitions, flying qualities are how the dynamics of the vehicle respond to control inputs. Handling qualities relates to the pilot opinion and the pilot interface (sticks, displays, force and displacement gradients) to how the aircraft responds. This effort focuses on what Key refers to as “flying qualities” given the intention to not develop full aircraft specific control systems and pilot models for the assessment process. By focusing on “flying qualities”, the resultant trends and conclusions should be applicable to an entire class of rotorcraft rather than a specific aircraft and flight dynamics model. Furthermore, the proposed work can generate guidance on operating UAS rotorcraft (i.e. FireScout and successors) to establish acceptable Ship-Helicopter Operating Limits since there is no pilot on board to distinguish between flying and handling qualities.

rotor radius and those that induce velocities larger than the wake induced velocity), how does a rotor respond to different size disturbances and how does the rotor type influence this? For example, in general, a rotor acts to filter the influence of a disturbance field, but the level of filtering will vary significantly between an articulated flexible rotor (H-60) and a gimbaled stiff one (V-22). Moreover, rotors typically respond $\sim 90^\circ$ out of phase of the disturbance, whereas fixed aerodynamic surfaces response directly in-phase, which results in a fundamentally different response between rotorcraft types (i.e. helicopter vs. tiltrotor).

2. How do these scales vary when the effects on the full aircraft are accounted for? The primary response from the helicopter will be dominated by that of the rotor, though there may still be significant response associated with the disturbance induced flow on the fuselage, empennage and tail rotor.
3. How do these scales vary with aircraft configuration/type (i.e. conventional helicopter vs. tiltrotor)? The primary response from the helicopter will be dominated by that of the rotor, whereas the tiltrotor may respond primarily in a fixed wing manner associated with the induced flow on the wing. Of course, the tiltrotor's response will also vary with nacelle angle, and it is well known that the V-22's response to wake disturbances (i.e. during formation flight) is quite different to other rotorcraft in the Navy's inventory [2].
4. How do these scales vary with aircraft flight condition, and can valid modeling simplifications be made (i.e. distorting vs. classical frozen disturbance field)? Work by Whitehouse and Brown for helicopter rotors [3-7] suggests that for high speed flight, the traditional frozen field (superposition) assumption may be adequate, but that at the low speeds associated with DI operations, a distorting disturbance field and wake are required because the response is critically different.

Developing an understanding of fundamental aircraft aeromechanic response, FD, and FQ to the unknowns outlined above would provide great utility to the community with regards to establishing the level of modeling fidelity required to accurately simulate disturbance interactions, the level of fidelity required to be output by CFD simulation generated ship airwake databases for training scenarios, and the quantification and specification of handling qualities to types of disturbance fields that can be used to define future and ongoing training and aircraft performance requirements and specifications, such as ADS-33 [8].

Introduction

Rotorcraft flight dynamics models are typically based on simplified component aeromechanics, requiring tuning to capture realistic response characteristics. DI introduces other difficulties such as partial ground effect and interactions between the rotorcraft wake and ship airwake. Reliance on overly simplified modeling and limited bodies of experimental data undermines the realism necessary for investigating the aeromechanics of new configurations and for effective training. For example variations on linear superposition with a frozen disturbance field are still used to represent the influence of the ship airwake and other flow-field effects on the aerodynamics, and thus flight dynamics of the aircraft even though such approaches were shown to be invalid for rotorcraft interacting with external disturbances more than 15 years ago [3-7]. An example of the types of distortions experienced by the rotor wake and the disturbance field (in this case an idealized wake vortex trailed from an aircraft wing tip) is shown in Figure 2. As will be discussed below, this prior work is significant because it attempted to breakdown the response² of a rotorcraft interacting with an external flow field to the most fundamental level by idealizing both the aircraft and the disturbance field; however, given the level of fidelity available at that time no attempt was made to investigate the full aircraft 6 degree-of-freedom FD response, FQs or HQs. Only recently, in work by Continuum Dynamics, Inc. (CDI) in collaboration with NAVAIR Flight Vehicle Modeling and Simulation Branch personnel, have evaluations of fully-interacting DI simulations been undertaken in a research trainer [9] (see Figure 3) and a production fleet trainer [10].

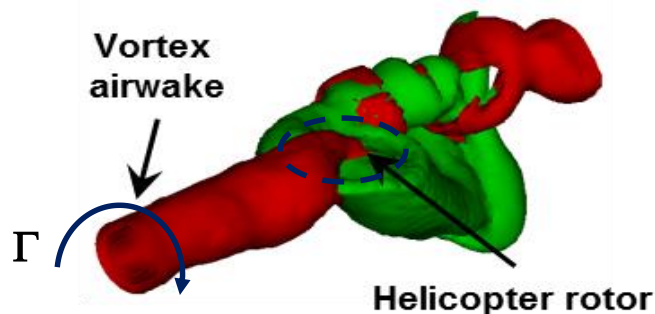


Figure 2: Predictions of interacting rotor wake (green) and airwake (red) with direction of rotation of the vortex and the location of the rotor disk in blue

Over the past few years, CFD has been used to improve the modeling fidelity of ship airwakes [11], with recent success in developing airwake databases for integration into fleet pilot trainers [12]. Development of such a database is a substantial undertaking, and may provide a higher fidelity model – subject to resolving the length and time scales that impact aircraft handling qualities. From a fundamental fluid mechanics standpoint, prediction of these flows will always require more fidelity until we can simulate the Kolmogorov scale directly; however, from FD and HQ standpoints a much coarser representation may be sufficient, or at least the fidelity of the stored airwake database can be coarser, rather than the resolution of the original CFD prediction. Exactly what that coarser representation looks like is unknown and current airwake database requirements [12] are an ad hoc compromise between perceived numerical storage availability, feasibility and intuition rather than a formal quantification based upon

²individual component response subject to changes in modeling assumptions and fidelity

aeromechanics, FQs and HQ.³ Indeed, CDI, the Navy and others have already begun investigating methods to reduce the storage and computational cost of accessing these databases. This effort seeks to address this unknown directly from a physical insight standpoint, since once the scales of the disturbance that impart significant influence on the aeromechanics are known, the specification of an airwake database, and indeed the level of fidelity of the trainer, can be defined exactly. Finer resolution will always provide more information with regards to high frequency vibration (assuming that the trainer has sufficient predictive fidelity), but at a minimum, the scales that influence flight dynamics and FQs must be present. It is worth noting that independent of the complicated DI problem, the fluid dynamic scales present in atmospheric turbulence, formation flight wake interactions and nearfield operations (wake vortices and flow around/near to buildings) that influence realistic FD and FQs are also unknown beyond qualitative measures associated with low fidelity models and anecdotal evidence from pilots.

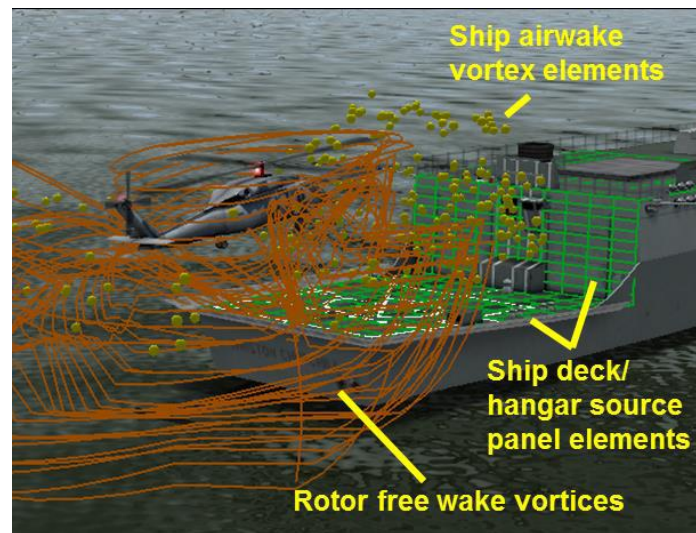


Figure 3: CASTLE / ExHel / CHARM visualization of shipboard operations

Rotorcraft Aeromechanics and Interactions with Disturbance Fields

Analysis of the response of rotorcraft to gusts, atmospheric turbulence and disturbance fields, such as ship airwakes, has generally followed practices derived from the fixed-wing community, focusing on frozen gust profiles superimposed onto aircraft aeromechanics [13] - i.e. the fields are fixed in space and do not distort/respond to the aircraft. The underlying assumption is that the time scales of the interaction are too short for such a mutual fluid dynamic interaction to occur [6], and indeed, ONR sponsored work at UMD/GIT [1] is investigating exactly this for canonical fixed-wing configurations.

Unlike their fixed-wing cousins, the response of a rotorcraft to external disturbances can be broken into two parts, namely, the response of the rotor, and the response of the airframe. When integrated together the, net response of the complete rotorcraft can be determined. Historically, the influence of gusts on the rotor has centered on ensuring the dynamic stability of the rotor system [14] and making first order estimates of the heave response to sharp edged gusts in order to quantify ride quality [13]. Rotor blade loading is usually much larger than the wing loading of conventional aircraft, and thus, since the heave damping derivative is inversely proportional to

³ Many ship airwakes are stored at frequencies up to 2Hz because this is the perceived bandwidth for pilot response, not aircraft or rotor response.

the blade loading, helicopter heave sensitivity is much lower than that for fixed-wing aircraft [13]. From a flight dynamics and handling qualities standpoint, estimates of the full six degree of freedom (6-DOF) derivatives can be similarly made, however, care must be taken to ensure that only the aerodynamic derivatives are used to determine “gains” related to gust response [13].

Such a derivative-based approach was a good fit with early rotorcraft flight dynamics simulations that applied simple stability derivative-based models. However, as rotorcraft became more complicated, the need to develop more sophisticated models for control law, control system development and training led to the adoption of a component build-up approach for aeromechanics models and FD simulations. In these simulations, each individual rotorcraft system/component is represented by a model that can be validated independently, and examples include GenHel [15] and the “example helicopter” model in NAVAIR’s CASTLE environment.

From an aerodynamics perspective, most modern rotorcraft FD models employ a blade element rotor model, with lifting-line/strip theory local aerodynamics coupled to a finite-state wake model; fuselage and empennage aerodynamics use a lookup table. The effective state-of-the-art in FD simulation employs a lifting surface blade aerodynamics model coupled to an unsteady vortex wake and panel method for the airframe [9, 10, 16]. CFD methods have been coupled to FD models of isolated rotors to study maneuvers (i.e. UTTAS) and DI scenarios [17], but full vehicle simulations using consistent (aerodynamic) fidelity across the aircraft components have not been performed due to computational cost.

The approach used to generate and represent the source of the rotorcraft gust model, or atmospheric disturbance, has taken a similar development route, with initial models following the fixed-wing paradigm of applying a frequency-domain linear statistical representation of atmospheric turbulence (determined by taking a PSD or Fourier transform of a suitable turbulence field – often the von Karman spectra or the Dryden “white noise” model [18]) as a frozen field. Extensions of this approach, such as Jones’ Statistical Discrete Gust method, enable more detailed representation of the structure of a gust since some of the gust’s phase information can be retained through the use of wavelets [13]. With the adoption of blade-element based aerodynamics models by the FD community, more sophisticated spatially accurate models of disturbance fields have been adopted by implementing analytical representations and 3D and 4D (space and time) look-up tables. Examples range from discrete vortices representing the wake (i.e. tip vortex) from a large fixed-wing aircraft implemented in research simulators [19, 20], to steady (3D) and unsteady (4D) ship airwake databases derived from CFD predictions implemented in operational flight trainers [12].

Despite significant advances in the level of realism in the disturbance field, and the acknowledgement that the assumption is fundamentally flawed when applied to rotorcraft [13], the vast majority of simulations still apply the frozen field model. Reliance on this assumption is predicated by the level of fidelity offered by contemporary analysis tools (i.e. they do not employ aerodynamics models capable of distorting the flow field)), but also by the prevalence of linear superposition in text books and papers when discussing the theoretical underpinnings of rotorcraft aeromechanics (i.e. [13, 21, 22]). Nevertheless, work over the past 15 years undertaken by the key personnel for this effort, and others, has shown a path forward that will form the basis of the work described here.

In the early 2000s, there was a resurgence of interest in more tightly integrating fixed- and rotary-winged aircraft into the civil airspace, and research in Europe investigated the impact of fixed-wing wake vortices on helicopter flight dynamics [3-7, 20, 23-25]. Padfield and co-

workers [20, 23-25] employed a conventional 6-DOF FD model of a Westland Lynx-like helicopter, with finite-state-wake, fuselage aerodynamic lookup table and frozen disturbance field, to determine that the helicopter's handling qualities could be significantly degraded and that the fuselage response could be large and important. Whitehouse and Brown [3-7] investigated the impact of the level of modeling fidelity used to represent the wake and the disturbance field on the aeromechanics of a generic isolated rotor interacting with a tip vortex from a large aircraft. The level of modeling fidelity ranged from analytical idealizations and traditional frozen field and finite state wake models, to fully distorting CFD models solving the Eulerian (grid-based) form of the incompressible Navier-Stokes equations in vorticity-velocity form. To quantify the effects of modeling fidelity in a consistent and rigorous manner, the flight dynamics of the model and the controls were constrained and the fundamental rotor aerodynamic and dynamic responses were calculated. Whitehouse and Brown concluded that when the wake and disturbance field interact over relatively long timescales, such as during low speed flight, the validity of the frozen field assumption must be called into question [6]. Predictions revealed that at low forward speeds the distortion of both the rotor wake and the disturbance field could be significant (see Figure 2), and that the severity of the rotor's response is reduced when compared to the frozen field case (see Figure 4). At high speeds, where the interaction time scale between the rotor wake and the disturbance field is much shorter, the frozen field assumption appears to be more appropriate; nevertheless, differences in the predicted thrust coefficient could vary by as much as 10% of the trim value.

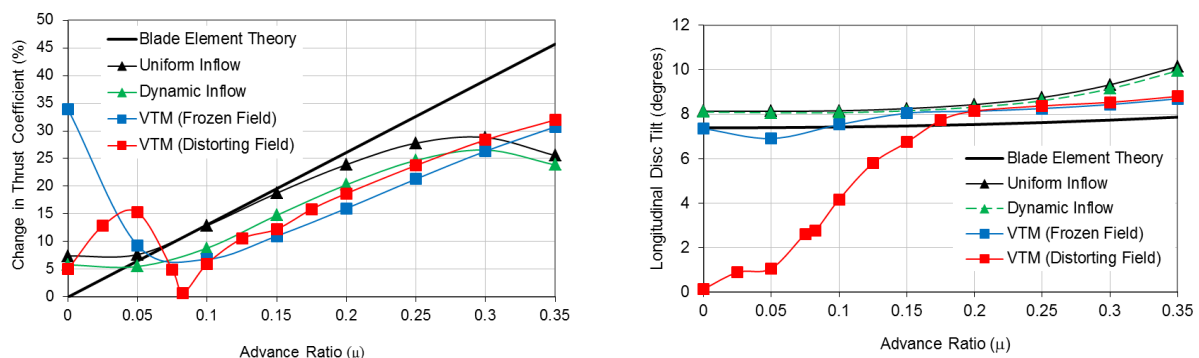


Figure 4: Mean perturbations to rotor thrust and longitudinal disc tilt for an isolated rotor interacting with a vortex aligned with the flight path. Adapted from [6, 7]

Around the same time in the United States, CDI started to use a distorting Lagrangian wake model to investigate multiple aircraft wake interactions in the terminal area for NASA [26]. This model built upon CDI's extensive history modeling aircraft wake vortices [27-32], and included FD models for a variety of configurations for preliminary safety assessment. This work was later extended under Navy sponsorship to investigate multiple aircraft shipboard operations [33]. More recently, this model was integrated into the Navy's CASTLE environment, and has been used by the Navy to plan and diagnose V-22 formation flight operations [2].

In recent years, several efforts of significance have demonstrated proof-of-concept for undertaking fully-coupled FD and disturbance field fluid dynamics predictions [9, 10, 17]. In [17], researchers at NAVAIR integrated the Kestrel CFD solver with CASTLE to simulate a helicopter landing on a ship. Due to computational cost considerations, the CASTLE blade element rotor model was used for the blade aerodynamics and to determine the strength of

appropriate momentum sources that should be inserted into the CFD grid to represent the wake. Kestrel then calculated the evolution of rotor wake and the ship airwake, including their mutual interference, and provided induced velocities to the blade model. No attempt was made to represent the helicopter fuselage or to undertake blade-resolved CFD; only qualitative results were presented. More recently, CDI, in collaboration with NAVAIR, interfaced the CHARM unsteady aerodynamics module (lifting surface blade aerodynamics model coupled to an unsteady vortex wake, panel method airframe and vortex particle disturbance field) with CASTLE and undertook fully-coupled simulations of a helicopter approaching and landing on a ship deck in both a research simulator [9] and a production (fleet) pilot trainer [10]. In the CDI approach, a ship-airwake database is used to initialize a vortex particle representation of the disturbance field. The Lagrangian vorticity-velocity form incompressible Navier-Stokes equations - the vorticity transport equations - are then solved to determine the mutual interaction of the rotorwake, the ship airwake and the fuselage. Like the work in [17], only limited qualitative metrics were presented, with comparisons made only to the baseline CASTLE model. While the work in [9, 10, 17] represents a significant advance in demonstrating what is feasible with regards to FD simulation for DI applications, these efforts did little to answer the key fundamental questions about aircraft response outlined above.

Unfortunately, while there have been significant strides in advancing aeromechanics modeling in recent years, the fundamental understanding of the response of rotorcraft to disturbance fields has advanced little since the early 2000s. The following quote from Whitehouse and Brown [6], dated 2004, remains just as pertinent today as it did then.

“Unfortunately, the wide variation in modeling techniques employed in the various published studies and the absence, in most cases, of any systematic variation in model parameters has made it difficult to organise the literature into a mutually-consistent body of evidence from which any general conclusions regarding the safety implications of helicopter encounters with aircraft wakes can be inferred. The situation is compounded by a singular lack of data against which these computations can be validated, and thus the possibility of model-dependence in some of the published results cannot be excluded. In particular, in most previous studies the mutually-induced distortion of the wakes of the rotor and the interacting aircraft has been neglected, yielding the so-called ‘frozen vortex’ assumption. This assumption has generally been adopted as a matter of computational expediency, but where the wakes interact over relatively long timescales, its validity must be called into question. Such is the case when the helicopter is operating at the low forward speeds that are characteristic of terminal flight operations.”

Indeed, it is exactly this need that the proposed effort seeks to address. Now, with rotorcraft aerodynamics prediction methodology in a flight dynamics environment at the point where both the disturbance field, the aerodynamic/wake model and the rotorcraft configuration can be varied in a systematic manner, courtesy of the recent CDI ONR effort (N00014-14-C-0014 – see [34, 35]), we are in a position to finally answer many of the fundamental handling qualities and flight dynamics questions outlined above.

Methods, Assumptions, and Procedures

Technical Objectives

The goal of the effort is to develop a fundamental understanding of the relationship between the length and time scales typically present in disturbance fields experienced by Naval aviators (i.e. ship airwakes, wing wakes etc.) and rotorcraft FD and FQ when the fully-interacting fluid dynamics of the airwake and rotor wake and flight mechanics are accounted for. With this information in hand, the engineering community would be better able to understand the relationship between aircraft type, ride quality, FD and FQ during flight conditions where disturbance fields are encountered. The community would be able to more accurately define trainer requirements, minimum experimental campaign requirements, minimum CFD modeling requirements and consequently establish a benchmark to evaluate CFD predictive capability. Furthermore, the conclusions of this work would also directly impact the development of requirements for new aircraft given the direct correlation between FD and FQ. The proposed effort would undertake the research required to develop such an understanding, with disseminating the observations and conclusions of the work to the Navy and the broader FD, FQ and handling qualities communities - a key objective from the outset. The effort will be structured using a build-up approach that first focuses on defining relevant disturbance fields followed by predicting and understanding the fundamental aeromechanics response (i.e. aerodynamic forces and moments and rotor dynamics). The effort would culminate in predicting the flight dynamics and handling qualities for realistic, but generic, helicopter and tiltrotor configurations that include representations of flight controls, propulsion system and cross-coupling characteristics. The key objectives for the effort roughly form the main tasks and are as follows:

1. Define the spatial and temporal fluid dynamic scales present in relevant disturbance fields and develop numerical representations for testing (Year 1).
2. 6-DOF generic model assembly and shakedown testing to ensure correct operation and functionality.(Year 1)
3. Define aeromechanics performance and HQ metrics along with a detailed simulation test matrix that includes systematic and consistent model fidelity build-up (Year 1-2).
4. Undertake simulation of a generic helicopter interacting with frozen and distorting disturbance fields to establish fundamental response characteristics (Year 2).
5. Undertake simulation of a generic tiltrotor interacting with frozen and distorting disturbance fields to establish fundamental response characteristics (Year 2).
6. Develop a realistic full helicopter model and undertake simulations of interactions with frozen and distorting disturbance fields to establish flight dynamics and handling qualities response (Year 3).
7. Develop a realistic full tiltrotor model and undertake simulations of interactions with frozen and distorting disturbance fields to establish flight dynamics and handling qualities response (Year 3).
8. Documentation and dissemination of observations and conclusions to the Navy and the wider FD/HQ community (Years 1-3).

The intention is that this effort be a natural, albeit rotor-centric, follow-on to the ONR sponsored work of Jones and Smith at the University of Maryland and Georgia Institute of

Technology respectively [1]. In their work, Jones and Smith are undertaking a combined experimental and numerical investigation of the aerodynamic loads induced on a wing by the wake shed from different canonical structures. The proposed effort seeks to leverage and complement that work by extending it to rotor systems and focusing on several fundamental unknowns related to how disturbance field spatial and temporal scales alter rotorcraft aeromechanics. A numerical approach is proposed because we feel that it is the most cost effective way to interrogate the underlying physics so that critical understanding of both the rotor response and the level of modelling fidelity required can be established. With this information in hand, an understanding of the flight dynamics and flying qualities (gust suppression) can be developed that will impact simulator development, dynamic interface training, operations and ship-aircraft suitability.

As summarized earlier, a rotor system responds to a disturbance field in a fundamentally different manner to a wing, with the typical response being $\sim 90^\circ$ out of phase to the disturbance and the amplitude filtered somewhat. There is a relative dearth of literature, and reproducible experimental data, related to the fundamental response of a rotor system to a large disturbance field, with studies either investigating full-up DI type scenarios (where the problem is so complicated that one is unable to unpack the fundamental physics from configuration specific nuances) or the type of disturbance field is generated by a relatively simple structure, but is difficult to model confidently and accurately in numerical methods, which results in an inability to differentiate the underlying physics from deficiencies/differences in the modelling choices made. For example, it would be convenient to use a cylinder, a cube or a backwards step to generate a disturbance field in a wind tunnel, but predicting/replicating the flow fields associated with these structures with CFD, even in the absence of a rotor, is technically challenging. Add in the need for an adequately instrumented rotor⁴ and the prospect of undertaking a high quality experimental test that can produce reproducible and archival quality data is potentially expensive and daunting.

⁴Minimum required measurements are integrated loads at the hub, the zeroth and 1st harmonic blade flapping, in addition to flow diagnostics (flow visualization and possibly PIV)

Results and Discussion

Work in FY24 focused on quantifying the fundamental influence of wake structures on rotorcraft and performing CASTLE simulations. Results are summarized here, and more details can be found in the final report.

Quantifying Fundamental Influence of Wake Structures on Rotorcraft

The influence of an arbitrary vortex wake structure on the fundamental response of a rotor can be derived using Blade Element Theory (BET) analysis [5, 7]. Detailed derivation of these equations is provided in Ref. [7]. We focus here on the assumptions made and resulting expressions.

Consider an “idealized” rotor with the following assumptions:

- No hub accelerations;
- Controls remain fixed;
- No hinge offset;
- Quasistatic response whereby the flap response of the rotor is much faster than the speed at which the vortex structure traverses the rotor; and
- Only the vertical component of the velocity associated with the arbitrary vortex is considered since it directly influences rotor inflow.

The influence of an arbitrary vortex with nondimensional vertical velocity $v_{vortex}(r, \psi)$, where r is the radial coordinate and ψ is the rotor azimuth, on rotor thrust coefficient C_T , coning β_0 , lateral disc tilt β_{1s} and longitudinal disc tilt β_{1c} is given by the following expressions [7]:

$$\begin{aligned} C_T &= C_T^* - \frac{Nca}{2\pi} \int_0^{2\pi} \int_0^R v_{vortex}(r, \psi)(r^2 + \mu \sin \psi) dr d\psi, \\ \beta_0 &= \beta_0^* - \frac{ca}{4\pi^2 \omega^2 I_\beta} \int_0^{2\pi} \int_0^R v_{vortex}(r, \psi)(r^2 + \mu r \sin \psi) dr d\psi, \\ \beta_{1s} &= \beta_{1s}^* + \frac{ca}{2\pi^2(\omega^2 - 1)I_\beta} \int_0^{2\pi} \int_0^R v_{vortex}(r, \psi)(r^2 \sin \psi + \mu r \sin^2 \psi) dr d\psi, \\ \beta_{1c} &= \beta_{1c}^* + \frac{ca}{2\pi^2(\omega^2 - 1)I_\beta} \int_0^{2\pi} \int_0^R v_{vortex}(r, \psi)(r^2 \cos \psi + \mu r \cos \psi \sin \psi) dr d\psi, \end{aligned} \tag{1}$$

where $()^*$ terms represent the responses without the vortex, N is the number of rotor blades, a is the airfoil lift-curve slope, c is the blade chord length nondimensionalized by rotor radius R , ω is the flap natural frequency nondimensionalized by rotor rotational speed Ω ($\omega = 1$ for zero hinge offset), and I_β is the blade flapping inertia nondimensionalized by ρAR^3 , where A is the rotor disc area. For a specified vortex velocity function $v_{vortex}(r, \psi)$, the corresponding influence on rotor fundamental response can therefore be quantified using the expressions in Eq. (1).

Rotor Fundamental Response To Isolated Vortex

As described at the beginning of the document, research on the impact of fixed-wing wake vortices on rotorcraft response motivated prior work [7], which investigated the effect of disturbance modeling fidelity on rotor fundamental response using idealized vortex representations. Fidelity levels for the interaction ranged from analytical idealizations and frozen field models to fully distorting CFD models solving the Eulerian form of the incompressible Navier-Stokes equations. Here we model a similar idealized vortex to examine the analytical responses given by Eq. (1) for the four helicopter rotors presented in Table 1. The idealized vortex is depicted in Figure 5 and represented using a modified Dreier[19] vortex from [7]

$$v_{vortex}/v_c = 1.359 \frac{r}{r_c} e^{-0.0001 \left(\frac{r}{r_c}\right)^4} \text{ if } 0 \leq \frac{r}{r_c} \leq 0.60653, \quad (2)$$

$$v_{vortex}/v_c = \frac{1 + \ln(r/r_c)}{r/r_c} e^{-0.0001 \left(\frac{r}{r_c}\right)^4} \text{ if } \frac{r}{r_c} > 0.60653,$$

where r represents the radial distance from the vortex center nondimensionalized by rotor radius R , r_c is the nondimensional viscous core radius and v_c is the peak tangential velocity of the core nondimensionalized by the product of rotor rotation speed Ω and rotor radius R . The associated velocity distribution is shown in Figure 6.

Table 1: Rotor properties considered in fundamental response analysis.

Vehicle	Number of blades	Chord [ft]	Radius [ft]	Rotation speed [rad/s]	GW [lbs]	Ibeta [slug-ft2]	Solidity	Disk loading [lbs/ft2]
MQ-8C Fire scout (Bell 407)	4	0.9	17.5	43.25	5400	143.8	0.065	5.6
UH-60	4	1.73	26.83	27	16500	1512.6	0.082	7.3
V-22	3	2.09	19	41.57	39500	721.6	0.105	17.4
CH-53E	7	2.44	39.5	18.53	60000	6744.7	0.138	12.2

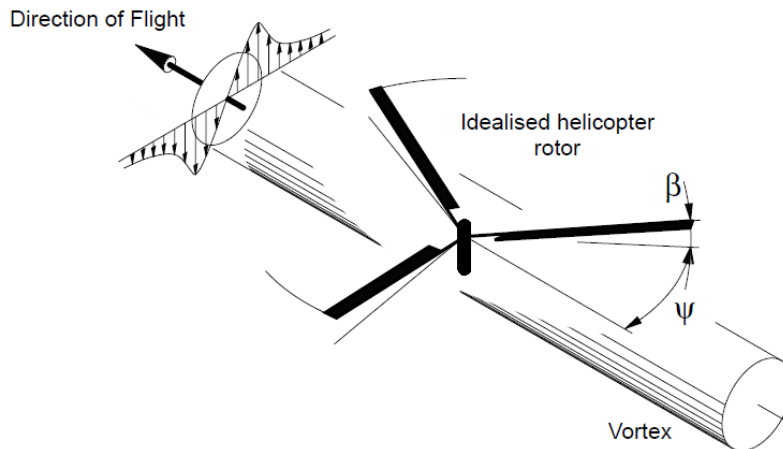


Figure 5: Depiction of idealized vortex [7].

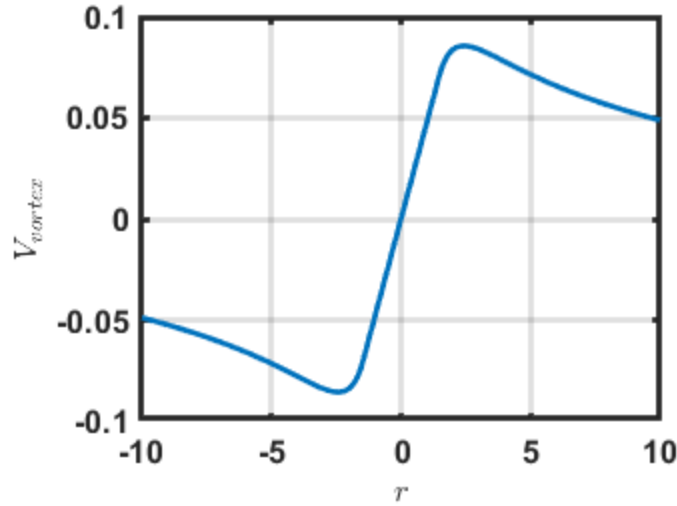


Figure 6: Idealized vortex velocity distribution.

It should be noted that vortex sign (direction) influences the results, with a positive vortex inducing a positive increase in thrust and flapping, and a negative vortex (the one considered here) inducing a decrease in thrust and flapping. Rotor responses following Eq. (1) for the rotors aligned with the vortex as shown in Figure 5 are shown in Figure 7 and Figure 8 for various values of advance ratio μ (forward speed nondimensionalized by ΩR). Similar to results from [7], the BET based analytical results predict a linear increase in response with increasing forward speed. It is also worth noting that the nondimensional blade loading parameter $\Delta C_T / \sigma$, where $\Delta C_T = C_T - C_T^*$ and σ is the blade solidity, “collapses” all the rotor analytical responses onto each other in Figure 8, highlighting its potential as a useful scaling parameter that can provide insights into fundamental rotor response to disturbances. In Figure 7, the MQ-8C and UH-60 rotor responses are close to each other, due to similar disk loading and solidity values (see Table 1). The validity of the trends seen in Figure 7 and Figure 8 will be tested using dynamic coupled airframe-rotor models later in the report, where we will investigate the influence of both frozen and distorting vortex effects using a Lagrangian disturbance modeling.

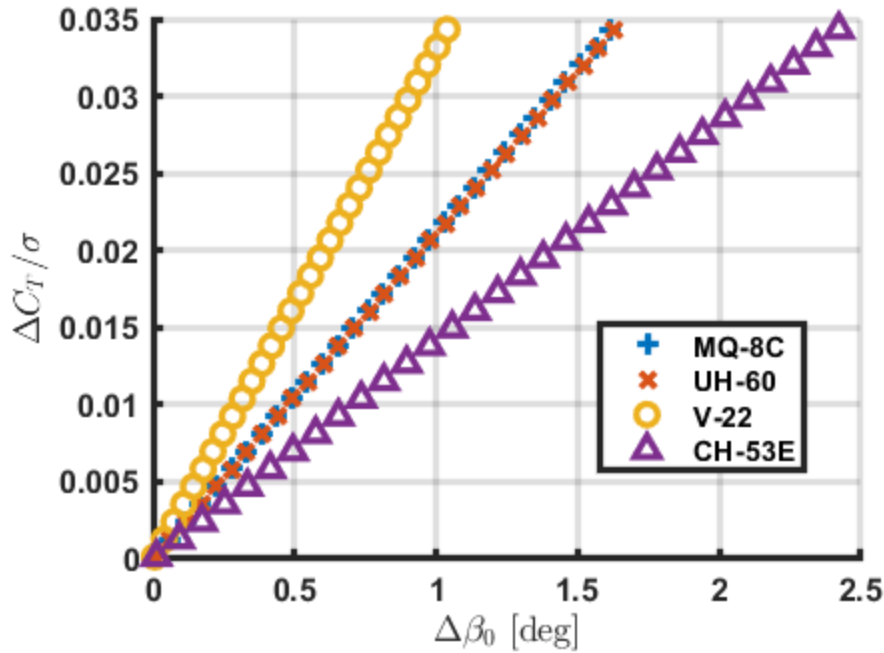


Figure 7: Influence of idealized vortex on rotor response for increasing advance ratios; $C_T^* = W/\rho(\pi R)^2(\Omega R)^2$, $\Delta C_T = C_T - C_T^*$, $\Delta\beta_0 = \beta_0 - \beta_0^*$.

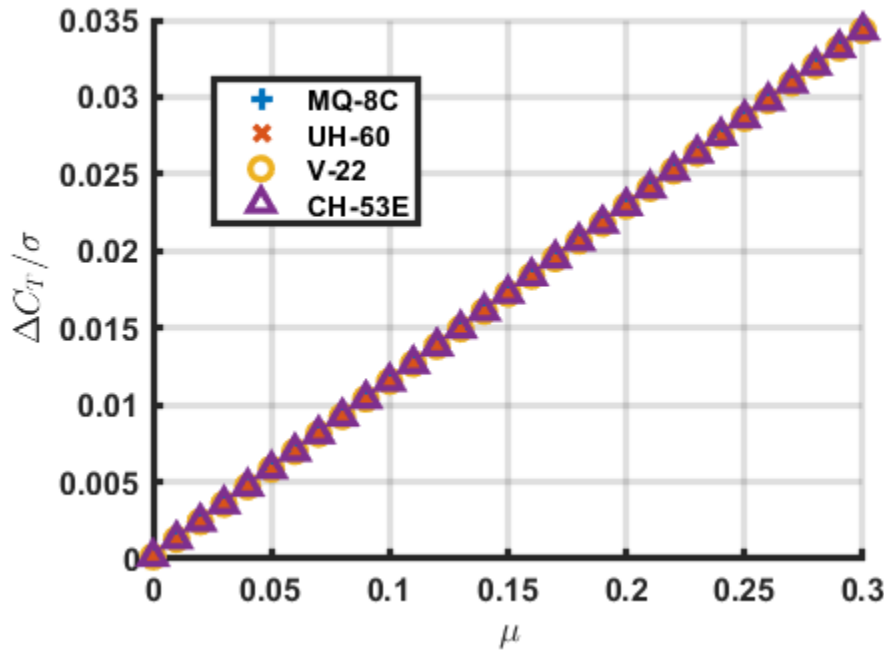


Figure 8: Influence of idealized vortex on rotor thrust coefficient for increasing advance ratios; $C_T^* = W/\rho(\pi R)^2(\Omega R)^2$, $\Delta C_T = C_T - C_T^*$, σ is blade solidity.

Rotor Fundamental Response To Arch Vortex Disturbance

In prior work, we derived a velocity model for the arch vortex that develops aft of rectangular obstacles in headwind flow. This model is equivalent to the function $v_{vortex}(r, \psi)$ from Eq. (1) and enables the computation of fundamental rotor response to the airwake velocities

associated with the arch vortex. For the fundamental response analysis, we consider the rotors in Table 1. The expressions in Eq. (1) are evaluated using the rotor properties from Table 1 and the arch vortex model. We consider two locations for the rotor hub center in our analyses: $[x,y,z] = [0, 8, -20]$ m (location #1) and $[x,y,z] = [0, 6, -25]$ m (location #2), both defined relative to the coordinate system where x points port, y points up and z points fore

The intensity of the arch vortex influence on the different rotors is depicted in Figure 9 for hover ($\mu = 0$). Points that lie furthest from the origin indicate the strongest influence. At location #1, the influence of the arch vortex on the smaller MQ-8C rotor is strongest, followed in order of decreasing influence by the UH-60A rotor, the V-22 rotor and the CH-53E rotor. At location #2, the MQ-8C is again the most affected rotor, but this time, we note a greater arch vortex influence on the responses of UH-60A and CH-53E rotors. The influence of ship airwake flow features on rotor responses is thus characterized by both rotor properties (size, number of blades etc.) and position. Contours of velocity predictions using the arch vortex model and CGE/VorTran-M over the MQ-8C and CH-53E rotors (smallest and largest rotors considered, respectively) at locations #1 and #2 are shown in Figure 10 and Figure 11, respectively, for reference. Reasonable agreement in velocity predictions is noted with the largest discrepancies noted for the vertical velocity predictions, as was noted previously as well.

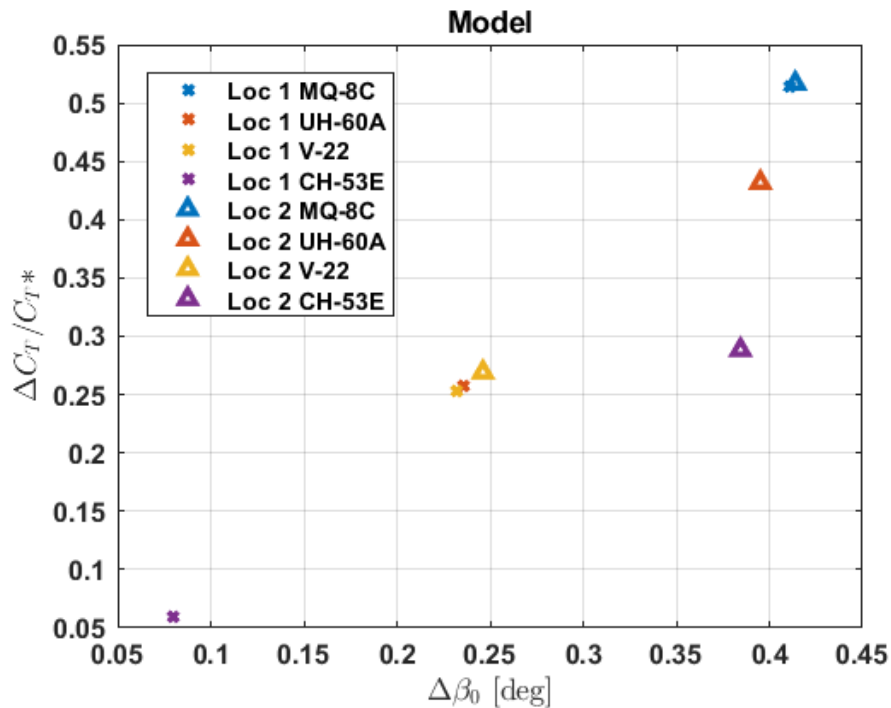
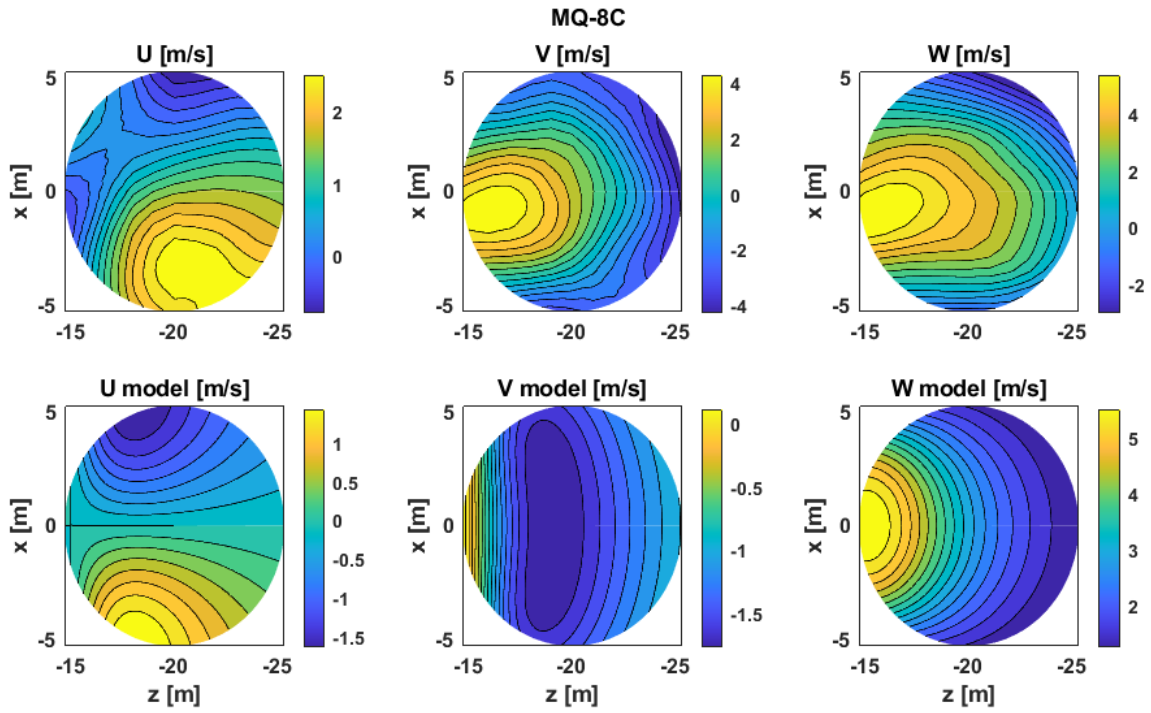
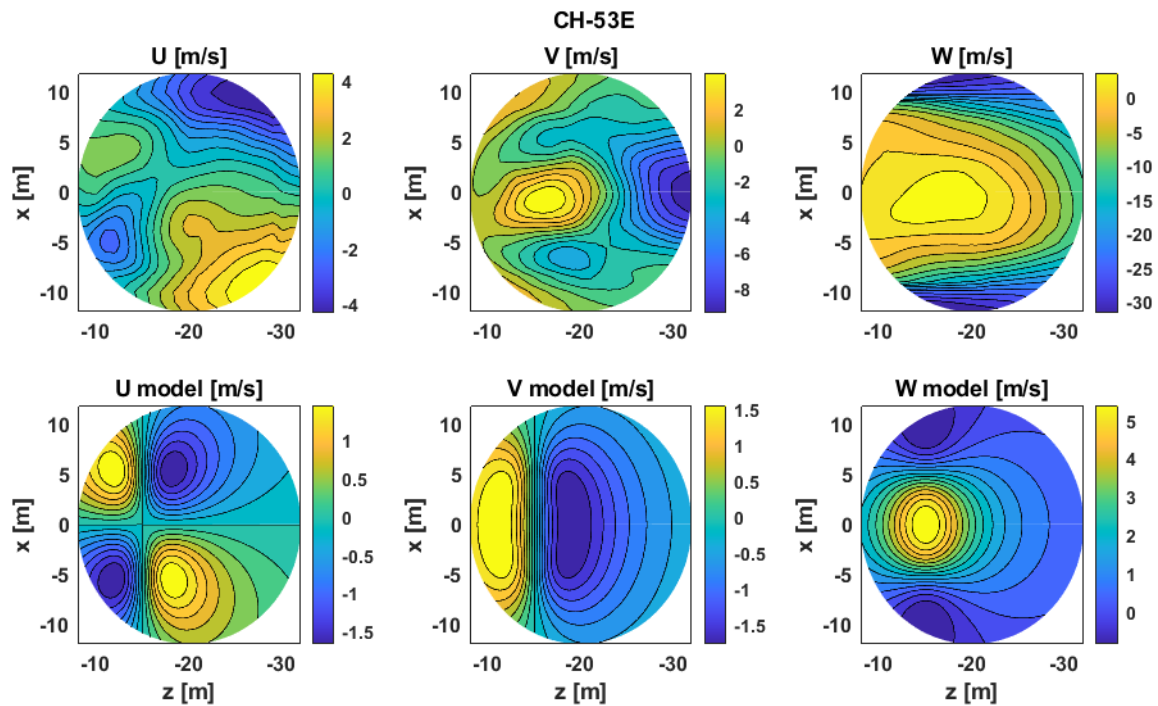


Figure 9: Influence of arch vortex on rotor fundamental response; $C_T^* = W / \rho (\pi R)^2 (\Omega R)^2$, $\Delta C_T = C_T - C_T^*$, $\Delta\beta_0 = \beta_0 - \beta_0^*$.

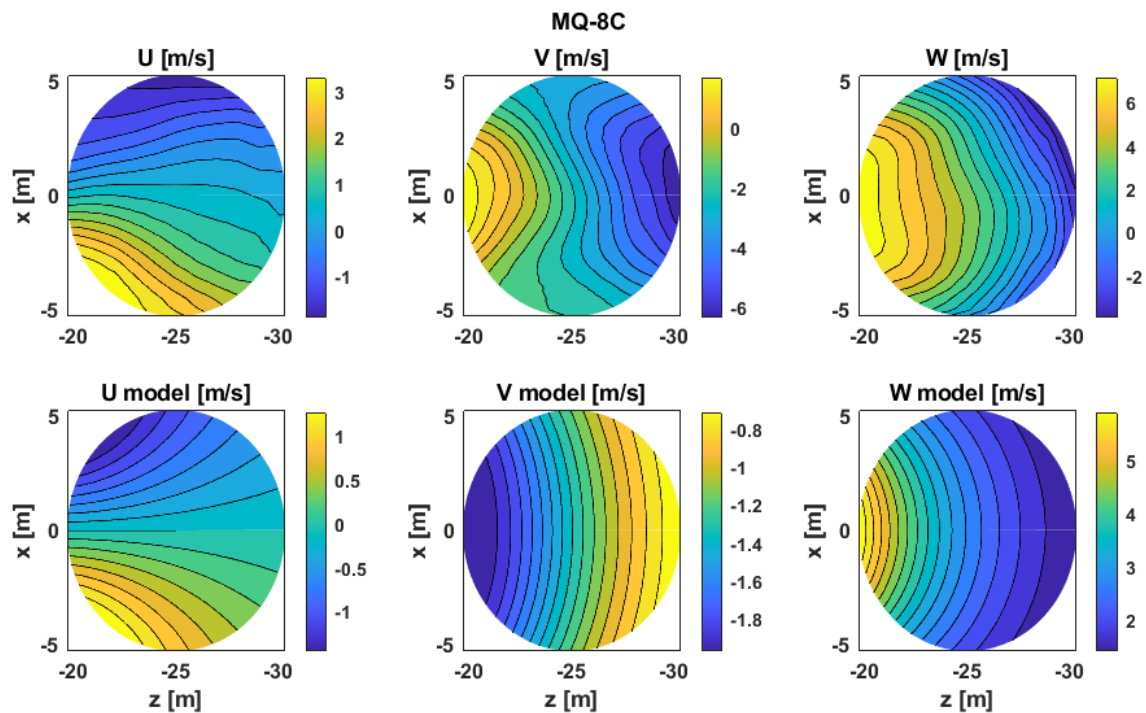


(a)

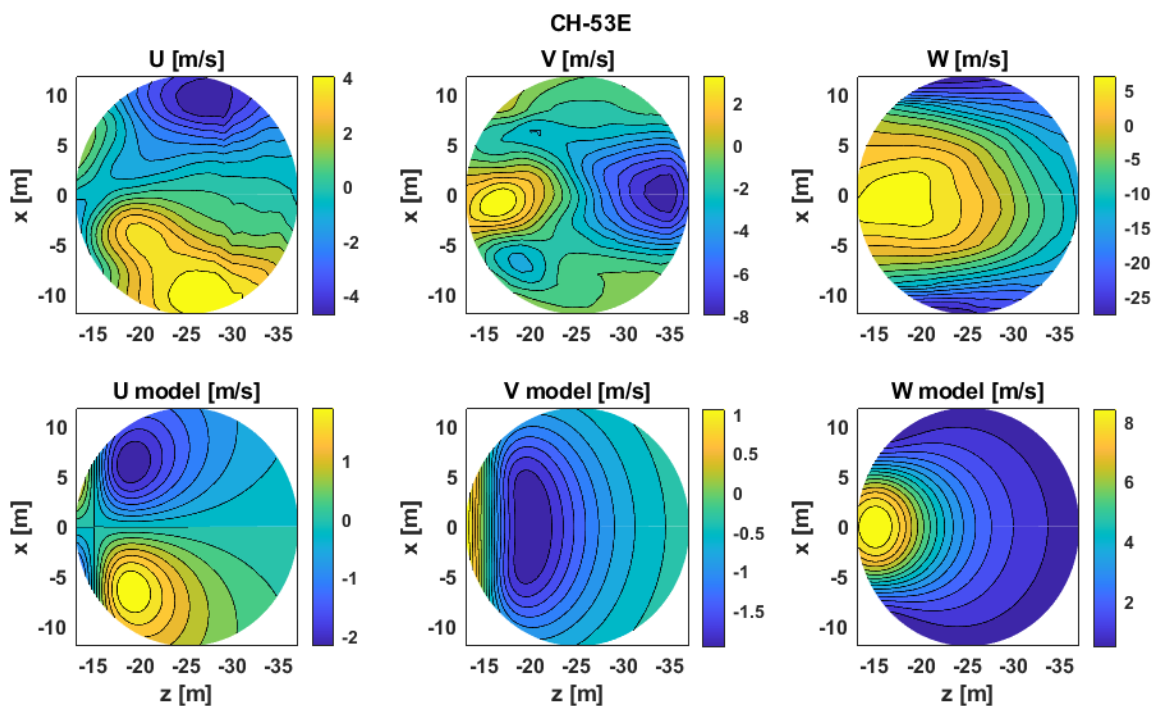


(b)

Figure 10: Contours of airwake velocity components over MQ-8C and CH-53E rotor centers at location #1 where $[x,y,z] = [0, 8, -20]$ m.



(a)



(b)

Figure 11: Contours of airwake velocity components over MQ-8C and CH-53E rotor centers at location #2 where $[x,y,z] = [0, 6, -25]$ m.

Rotor Fundamental Response in a Representative Approach trajectory

The arch/horseshoe vortex model is equivalent to the function $v_{vortex}(r, \psi)$ from Eq. (1) and enables the computation of fundamental rotor response to the associated airwake velocities. We again use the rotors from Table 1, and assume they follow a straight-line approach trajectory with a constant flight path angle $\gamma = 6^\circ$ (see Figure 12). The rotor hub centers coincide with the ship centerline. The descent begins at an altitude $y_0 = 45.7\text{m}$ (150 ft.) with a forward speed $V_0 = 41.2\text{ m/s}$ (80 kts), and ends in hover at an altitude $y_f = 6\text{m}$ (19.7 ft) above the center of the deck ($z=-20\text{m}$). We use the analytical model developed by Heffley [36] to determine the velocity and deceleration profile during this descent. This model provides velocity and deceleration expressions that are based on a human pilot's perception of the visual field during a deceleration operation from forward flight to hover and have been validated against flight test data [36]. The descent trajectory, velocity and deceleration profiles are plotted in Figure 13.

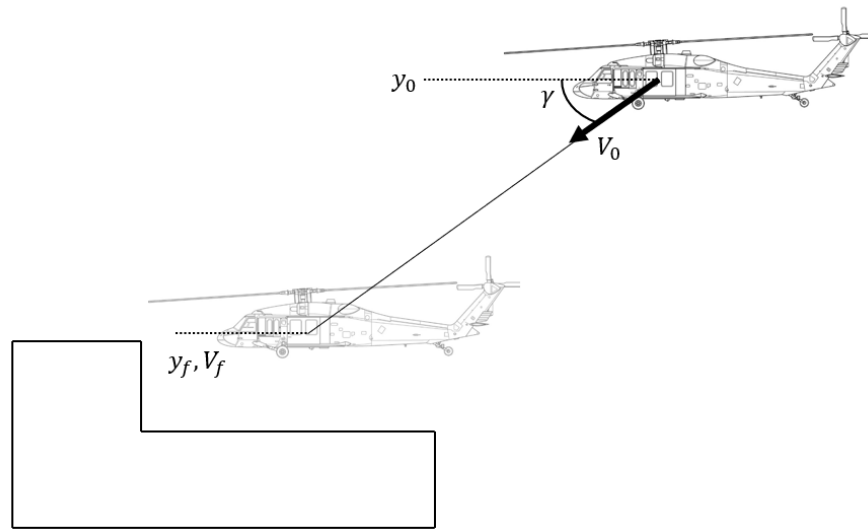


Figure 12: Illustration of approach trajectory.

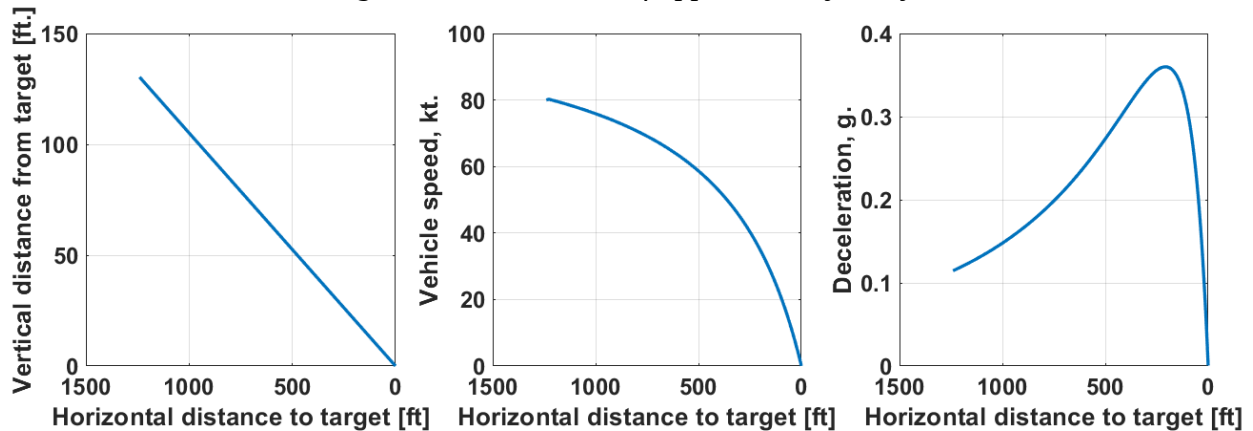


Figure 13: Approach trajectory (left), velocity (middle) and deceleration (right) profiles.

The magnitude of the horseshoe vortex influence on the thrust coefficient (C_T), disk coning (β_0) and longitudinal disk tilt (β_{1c}) as a function of nondimensional horizontal distance from the target location ($\bar{D} = D/L_a$) for the different rotors is depicted in Figure 14. Similarly, the influence of the vertical velocities obtained from CFD are given in Figure 15. Note that the

change in lateral disk tilt (β_{1s}) is negligible due to symmetry of the low-speed approach and the vortex model and is thus not shown here. We make the following observations from the figures:

1. There is a steeper decrease and kinks in responses near the target location ($\bar{D} = 0$) in Figure 14 since that is close to where the horizontal part of the horseshoe vortex is situated ($z=-14\text{m}$).
2. In both Figures, the MQ-8C rotor experiences the greatest change in thrust coefficient, followed by the UH-60 rotor. In Figure 14, we note that the V-22 rotor experiences a slightly greater change in thrust coefficient than the CH-53E rotor, while in Figure 15 the opposite is true, with a clear distinction in the response curves. This is likely due to the influence of additional flow features in the “truth” data in Figure 15, in addition to the rotor properties and size. This difference is under further investigation.
3. A greater response in coning magnitude is noted in the truth responses in Figure 15, when compared to those in Figure 14. Apart from the CH-53E coning response, the coning response of the MQ-8C rotor is the largest, followed sequentially by that of the UH-60 rotor and the V-22 rotor in both figures, which gives further confidence in the horseshoe vortex model approach.
4. For the longitudinal tilt response, the CH-53E rotor is noted to have the largest response away from the target location for $\bar{D} \in [1,2]$ and smallest response closer to the target hover location. In both Figures, the β_{1c} response for the MQ-8C and V-22 rotors appear to overlap, with that of the UH-60 overlapping with them as well in Figure 14.

These results are encouraging and indicate further showcase the potential impact of the horseshoe vortex as a fundamental airwake flow feature that influences aircraft responses.

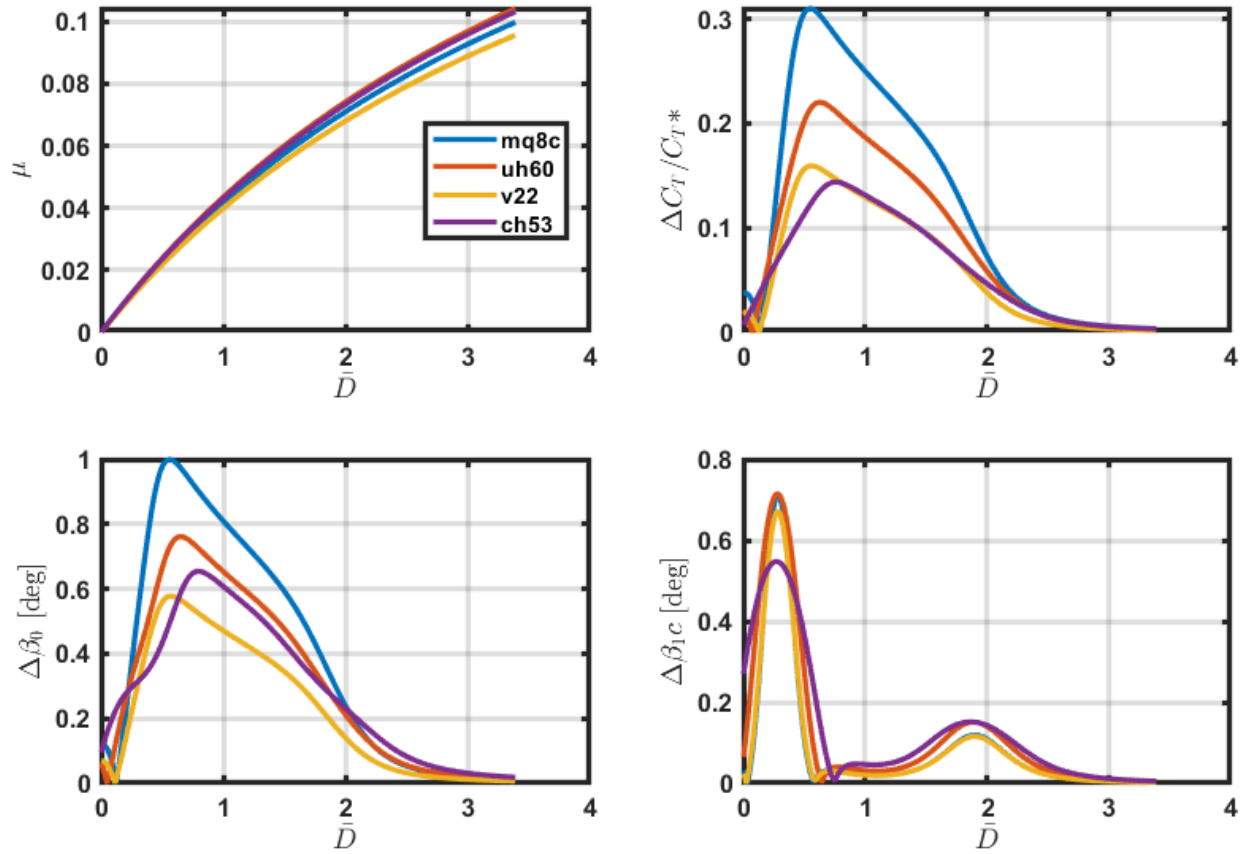


Figure 14: Advance ratio $\mu = V/\Omega R$ (top left), change in thrust coefficient (top right), change in coning (bottom left) and change in longitudinal tilt (bottom right) during approach to target hover position in the presence of horseshoe vortex; $C_T^* = W/\rho(\pi R)^2(\Omega R)^2$, $\Delta C_T = C_T - C_T^*$, $\Delta \beta_0 = \beta_0 - \beta_0^*$.

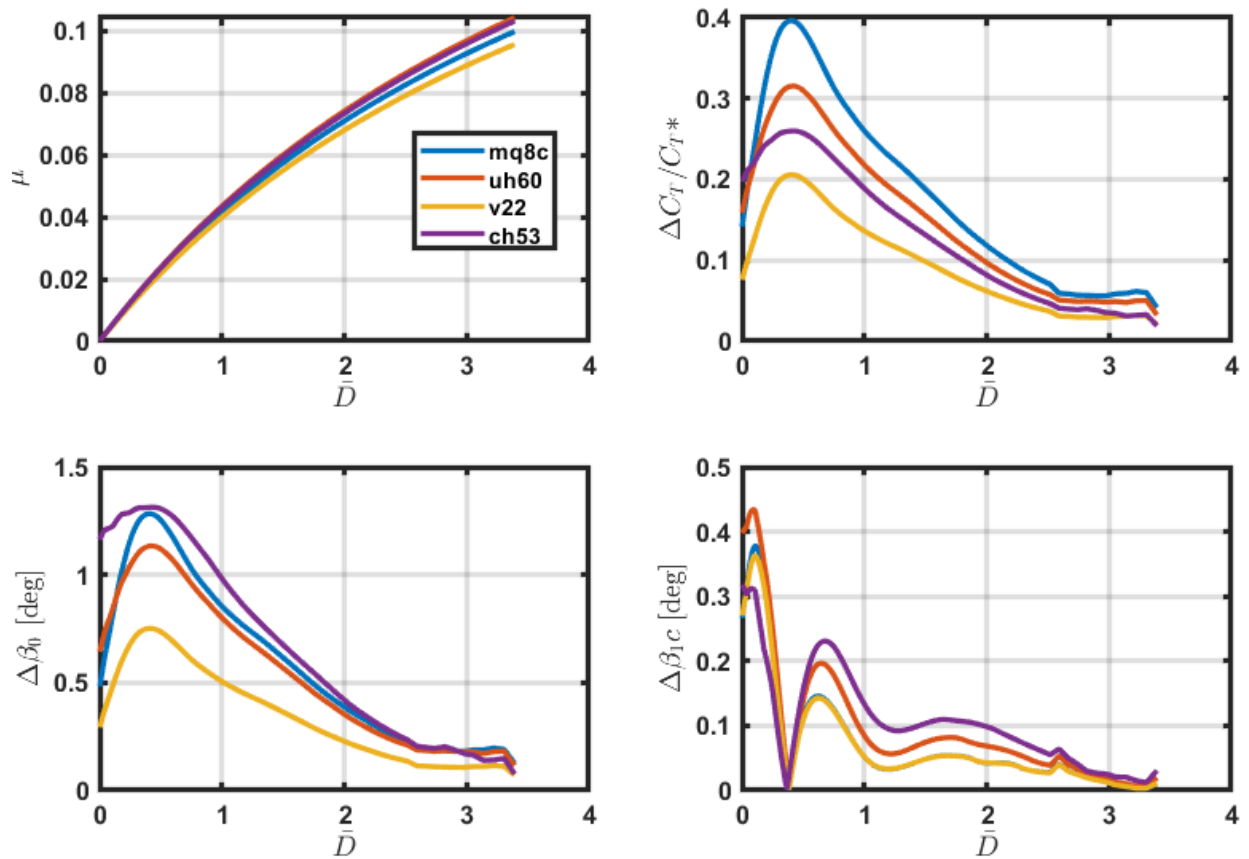


Figure 15: Advance ratio (top left), change in thrust coefficient (top right), change in coning (bottom left) and change in longitudinal tilt (bottom right) during approach to target hover position in the presence of CFD predicted vertical velocities; $C_T^* = W / \rho (\pi R)^2 (\Omega R)^2$, $\Delta C_T = C_T - C_T^*$, $\Delta \beta_0 = \beta_0 - \beta_0^*$.

Nondimensional Rotor Responses to Simplified Representation of Ship Airwake

The horseshoe vortex parameterization that we adopted relies on ship geometry dimensions (hangar height H , beam W) and freestream speed for dimensionalization. This representation, together with the analytical rotor response model given by Eq. (1), allows us to investigate the influence of varying ship geometry, freestream, and rotor properties (see Table 1) on rotor fundamental response, from which nondimensional scaling trends can be identified. We examined the following cases using the 4 rotors considered previously:

- Effect of varying ship beam;
- Effect of varying rotor vertical position; and
- Effect of varying free stream speed.

Baseline ship geometry dimensions consisted of $H = 12\text{m}$ and $W = 26\text{m}$ (the average for LPD, DDG, and LSD ships). A freestream speed of 15.4 m/s (30 knots) was assumed. All rotors are assumed to be in hover and positioned in plane with the horseshoe vortex, downstream of the horizontal part of the vortex. The hub centers lined up with the center of the vortex.

Effect of Varying Ship Beam

The influence of ship beam variation is shown in Figure 16. The quantity λ^* in the Figure represents a nondimensional measure of the inflow induced by the vortex, computed using momentum theory for a rotor in axial climb, and given by:

$$\lambda^* = \frac{\Delta C_T}{\sqrt{2C_T^*}} \quad (3)$$

where C_T^* is the baseline thrust coefficient of the rotor in hover determined using gross weight and $\Delta C_T = C_T - C_T^*$ (see Eq. (1)). From Figure 16, all the responses follow a bell-curve pattern, with peak inflow noted when ship beam $W \cong 1.3R$. The offsets in λ^* responses for the four rotors point towards the existence of an additional scaling factor that can “collapse” all the responses onto each other. For reference, Table 2 summarizes ship beam-to-rotor radius ratios for the four rotors and three (LPD, DDG, and LSD) ships.

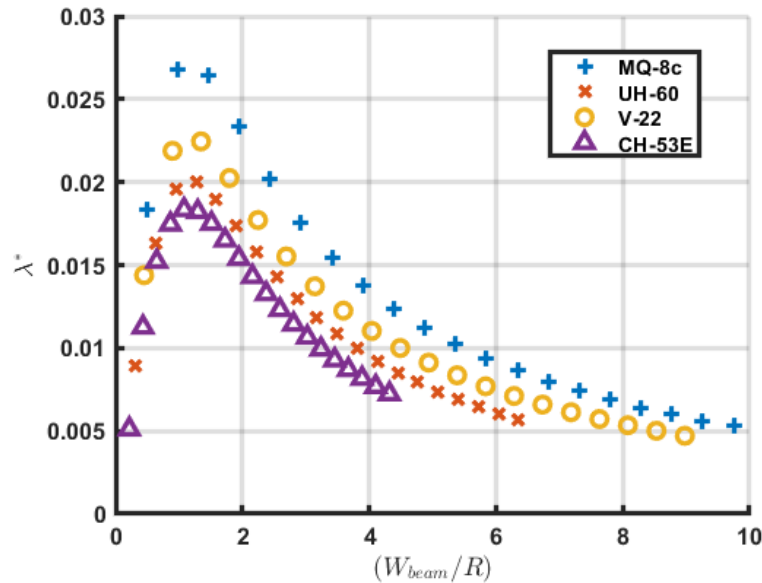


Figure 16: Influence of ship beam variation on rotor fundamental response; $\lambda^* = \Delta C_T / \sqrt{2C_T^*}$, where $C_T^* = W / \rho(\pi R)^2(\Omega R)^2$, $\Delta C_T = C_T - C_T^*$

Table 2: Representative ship beam-to-rotor radius values.

Ship	W [m]	W/R (MQ-8C)	W/R (UH-60)	W/R (V-22)	W/R (CH-53E)
LPD	32	6.0	3.9	5.5	2.7
DDG	26	3.7	2.4	3.5	1.7
LSD	32	4.9	3.2	4.5	2.2

Effect of Varying Rotor Vertical Position

The influence of rotor vertical position variation is shown in Figure 17, where we plot the nondimensional change in blade loading $\Delta C_T/\sigma$ against changes in vertical position Δy , which is nondimensionalized by hangar height H . All the responses follow the same trend and are close to each other, highlighting blade loading as a viable scaling parameter. Peak offsets in the responses are noted when the rotor is in line with the vortex ($\Delta y = 0$), where the MQ-8C and UH-60 responses and the V-22 and CH-53E responses overlap, respectively. Given the horseshoe vortex structure, the rotors experience peak disturbance when they are in line with the vortex.

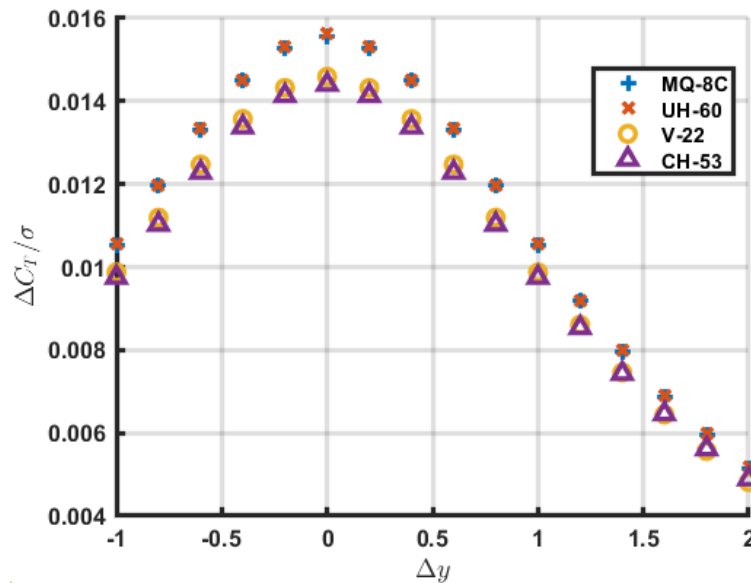


Figure 17: Influence of rotor vertical position variation; $\Delta C_T = C_T - C_T^*$, where $C_T^* = W/\rho(\pi R)^2(\Omega R)^2$, σ is the rotor solidity and Δy represents the change in vertical position from the starting position and nondimensionalized by hangar height H .

Note that the magnitude of the rotor responses to the disturbance scales linearly with freestream speed since this quantity scales the vortex strength accordingly. The two cases considered indicate the existence of scaling parameters such as λ^* or $\Delta C_T/\sigma$ that can be used to acquire initial insights into aircraft responses solely based on ship geometry and freestream. We further ascertain the applicability of these scaling parameters below using full aircraft dynamic simulations in CASTLE/CHARM for various airwake interaction levels.

CASTLE Simulations

CASTLE/CHARM Coupling for Simulating Rotorcraft Responses to Disturbances

The simulation environment to capture rotorcraft response to disturbances is built upon the NAVAIR CASTLE software, which provides a generic simulation executive and model development tools. CASTLE is structured so that simulation development requires specification of aircraft-unique models for aerodynamic loads, engine/transmission, weight/balance, control laws, and sensor models. CASTLE also provides a user interface and scripting (macro) language to perform various simulation functions and automation of simulation tasks.

The CHARM software is a well-validated comprehensive aircraft aerodynamics and dynamics analysis applicable to a wide range of fixed- and rotary-wing aircraft [37, 38]. CHARM couples a full-span, free-vortex wake model with a vortex lattice lifting surface blade model (VLM) and a fast doublet panel fuselage model to provide a capability for modeling complete aircraft aerodynamics involving combinations of propellers, rotors, wings, fuselages, and tail surfaces. CHARM exists as a standalone analysis capability and in the form of modules that can be integrated with existing simulation frameworks for specific computations. For integration with CASTLE, the CHARM wake panel module that specializes in computing induced velocities for specified aircraft components and spatial locations is used.

While CASTLE provides basic simulation executive functions, CHARM is integrated within the FVMS Models codebase, which provides a collection of re-usable code and tools for building the simulation model components. The FVMS Models library includes physics models (weight/balance, power plant, landing gear); environment models (airwake); systems models (sensors, avionics); and math utilities including coordinate transformations, conversion constants, general function tables and interpolation functions, and control system components. This library of generic models is coded in C++ and has been developed to provide a common codebase for validated (documented) models and simulation construction tools.

The FVMS physics models include a generic blade element model for application to rotary-wing aircraft simulations. The FVMS rotor system model is structured similarly to conventional rotor blade element models (such as GenHel [15]). This blade element model includes a distributed air loads calculation based on two-dimensional sectional aerodynamic data; rigid blade flap/lag dynamics; a simplified (empirical) dynamic twist correction; and inflow dynamics using the Pitt-Peters inflow model [39, 40]. The FVMS rotor system supports multiple rotors with different rotational speeds so that tandem, side-by-side (tiltrotor), and main rotor/tail rotor aircraft configurations can be modeled. Optionally, a simplified Bailey model may be used for the second (tail) rotor system.

The rotor system model for a specific aircraft simulation implementation can be developed by deriving from code components (base classes) defined in the FVMS codebase. It is during this development process where aircraft configuration-specific parameters are defined. Note that the base FVMS rotor system model includes all necessary executive functions for performing rotor trim and run mode operations. The inflow model is one component of a complete rotor system definition; it is at this level that the CHARM wake model is coupled.

The CHARM model (module) is integrated with the CASTLE / FVMS Models library using a separate interface class (C++ wrapper) that executes the free vortex wake and induced velocity model (function calls) in an external (dynamically linked) library. The FVMS/CHARM interface class maps simulation variables to CHARM variables, and vice versa, in addition to performing wake model initialization, update, and induced velocity evaluations.

In contrast to conventional dynamic inflow model formulations, the CHARM model provides induced velocity evaluations for control points corresponding to blade segments of multiple interacting rotors and for evaluation points off the rotor system (i.e., at aerodynamic control points at the empennage, lifting surfaces, and fuselage). Wake elements from multiple rotors, as well as fixed lifting surfaces, are fully interacting with each other and the surrounding environment (e.g., ground effect). Thus, the FVMS/CHARM implementation provides an induced velocity for the entire rotor system and airframe. Empirical “interference factors” used

in conventional rotorcraft flight dynamics simulations are replaced by direct (dynamically varying) wake induced velocity evaluations.

To account for rotor wake and ship airwake interactional effects, the interface of the ship airwake model component needs to be adapted. In a more conventional rotorcraft simulation formulation, rotor inflow and ship airwake effects are treated independently since their effects are superimposed in the blade aerodynamic calculation. Given the nature of the coupled rotor wake/ship airwake model, ship airwake velocity evaluations must be managed by the CHARM model to properly account for rotorcraft and ship airwake interactions. This approach allows different levels of airwake model coupling to be supported (e.g., rotor wake/airwake superimposition, airwake effects on rotor wake only, and fully-coupled rotor wake/airwake interactions) while ensuring that airwake effects are not double-counted. To support a generalized ship airwake interface to the CHARM model, an external airwake model “loader” interface (denoted SHIPWAKE) was previously developed. This external interface adopts a “plug-in” software architecture so that the specific airwake model (library) can be specified as a run-time parameter.

To provide an internal test environment for the coupled CASTLE/FVMS and CHARM models, the FVMS codebase has been applied to CASTLE’s Example Helicopter (or ExHel) simulation. The ExHel model is based on data describing the UH-60A helicopter, using a combination of equations and software developed for the FVMS Models codebase and original GenHel math model [15]. Note that the ExHel model is not intended to be a comprehensive simulation of an H-60 helicopter but to provide a representative conventional main/tail rotor helicopter configuration for research, tool integration, and training simulation engineers.

As part of the present effort, we revamped and tested out the enhanced ExHel simulation environment. We introduced a uniform 10 ft/s downwash disturbance field to the model in hover using the same input file format as would be required for a CFD based ship airwake data file to ensure proper execution and debug any workflow issues. The ExHel simulation provides the user with options to include a basic stability augmentation system (SAS) and/or an automatic flight control system (AFCS). For the initial results presented below, both are activated. The roll and pitch attitudes of the aircraft in the presence of disturbance are shown in Figure 18 for three cases: Pitt inflow model (no disturbance), CHARM inflow model (no disturbance), CHARM inflow model with two-way coupled airwake. As evident from the figure, choice of inflow and inclusion of the disturbance influences the aircraft attitudes, even in the presence of the SAS and AFCS, highlighting the importance of performing dynamic interface studies. The corresponding swashplate control inputs are shown in Figure 19. The main rotor collective θ_0 remains constant throughout the simulation because there is no control feedback associated with it that is implemented in the SAS or AFCS of the Exhel model. The remaining three controls are the ones used to maintain the trim flight condition in the presence of the disturbance. The influence of disturbance is also evident in the vertical force generated by the main rotor and shown in Figure 20. Note that the UH-60 tail rotor has a 20° cant angle from vertical to assist with lift. When the CHARM inflow is used, the tail rotor generates more lift than when the Pitt inflow model is used to sustain the hover flight condition as evident in Figure 19, where the starting value of the tail rotor collective for cases with CHARM included is higher than that with the Pitt inflow model.

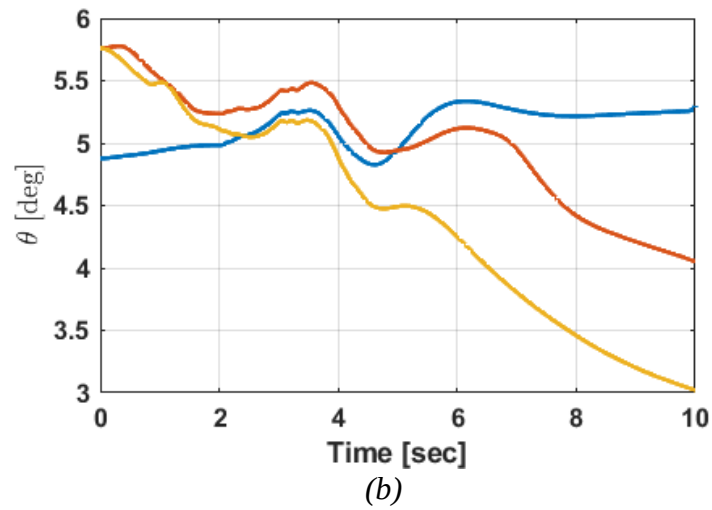
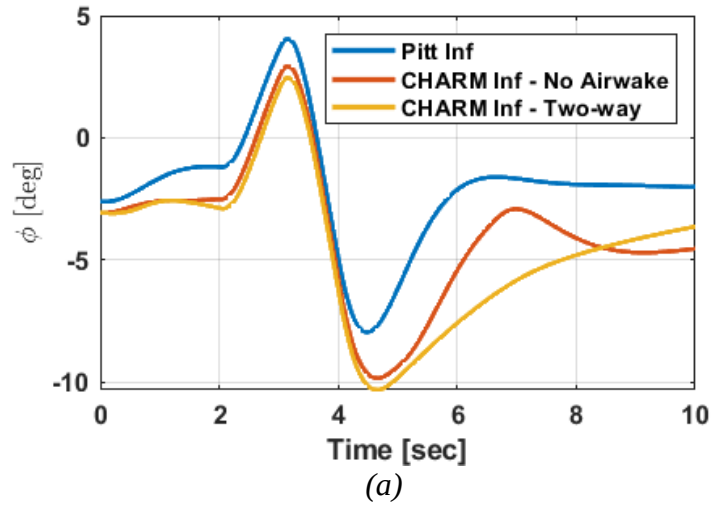


Figure 18: (a) Roll and (b) pitch attitude responses of CASTLE Exhel model to a uniform 10 ft/s downwash disturbance field in hover for three cases: Pitt inflow model (no disturbance), CHARM inflow model (no disturbance), CHARM inflow model with two-way coupled airwake.

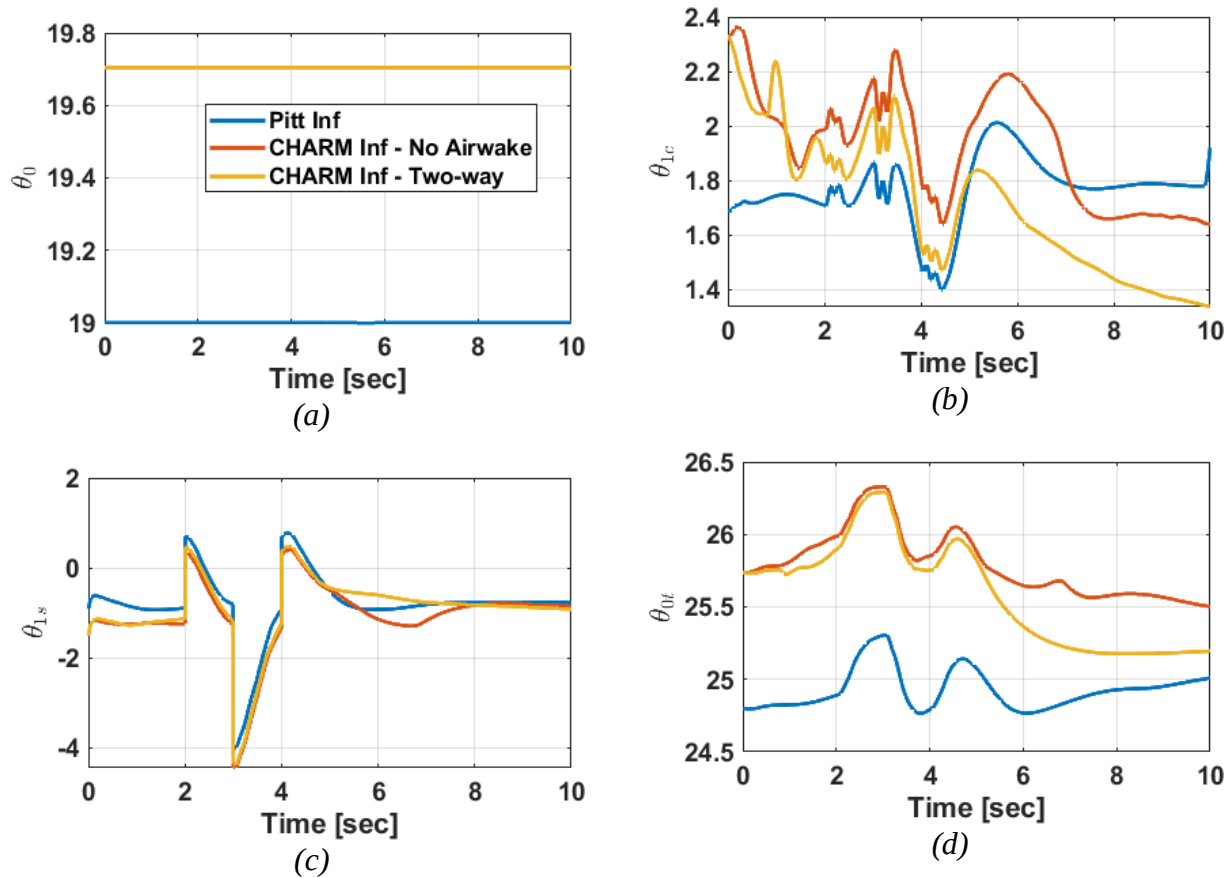


Figure 19: Time histories of main rotor swashplate (a) collective, (b) lateral cyclic, (c) longitudinal cyclic and (d) tail rotor collective inputs in the presence of a uniform 10 ft/s downwash disturbance field in hover for three cases: Pitt inflow model (no disturbance), CHARM inflow model (no disturbance), CHARM inflow model with two-way coupled airwake.

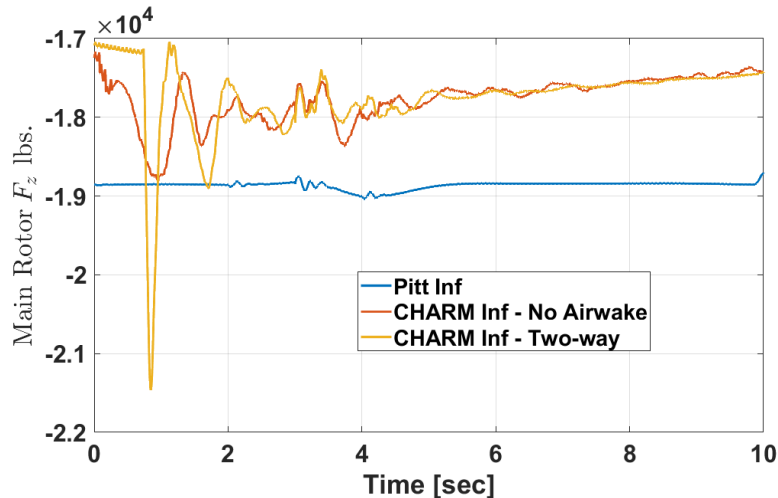


Figure 20: Time histories of main rotor vertical force in the presence of a uniform 10 ft/s downwash disturbance field in hover for three cases: Pitt inflow model (no disturbance), CHARM inflow model (no disturbance), CHARM inflow model with two-way coupled airwake.

Aircraft Response to Isolated Vortex Disturbance

We previously examined analytical responses of the four rotors given in Table 11 to the isolated vortex depicted in Figure 5. From this idealized investigation, blade loading $\Delta C_T/\sigma$ was indicated to be a potential scaling parameter for gaining insights into how rotor fundamental response scales with forward speed μ . Additionally, prior work on the topic [7] had questioned the applicability of the frozen field assumption, where the velocity fields are fixed in space and do not distort/respond to the aircraft, for low-speed flight. The basis for that was a series of investigations where the level of modeling fidelity for the disturbance ranged from analytical idealizations (like the one considered above) and frozen field models to fully distorting CFD models solving the Eulerian form of the incompressible Navier-Stokes equations. Results, see Figure 4, indicated that the frozen field assumption underpredicted the change in thrust but overpredicted the flapping responses at low forward speeds. In this section, we perform similar investigations using the ExHel model and CASTLE/CHARM coupling, which, unlike the prior isolated rotor investigations, includes fully coupled rotor-airframe dynamics and employs a distorting Lagrangian wake model. Simulations were performed with the rotor hub center aligned with the vortex center as depicted in Figure 5. For each forward speed considered, the aircraft was first trimmed without disturbance. Time-marching simulations were then performed with the disturbance turned on for a duration of 30 seconds. Results presented below employ time-averaged values. Given our focus on fundamental response, the aircraft position was held fixed during the time-marching simulation. We considered two gross weight values for comparison: 15,000 lbs. and 20,000 lbs.

Main rotor responses are shown in Figure 21 and Figure 22. Figure 21 shows that the vortex induces large changes in thrust at hover in both cases, with the lighter model experiencing changes close to 40%, which is greater than the change induced in the 20,000 lbs. model by approximately 15%. With increasing forward speed, the changes in thrust coefficient between the two models become closer. For the 15,000 lbs. model, one-way coupling of the vortex induced velocities results in conservative thrust changes at all forward speed values tested, except for hover, where the change in thrust is approximately 5% less than that obtained with the distorting model, and $\mu = 0.15, 0.2$, where the change in thrust is similar for both modeling

fidelities. For the heavier aircraft, the trend is similar at hover. However, with increasing forward speed, the frozen field model first provides a conservative estimate of the changes in thrust up to $\mu = 0.15$, beyond which the influence of the vortex is increasingly underpredicted relative to distorting model. The results in Figure 21 point towards the existence of relationship between modeling fidelity requirements, forward speed, and aircraft weight, where the frozen vortex assumption provides a conservative estimate of changes in thrust for “lighter” vehicles, but underpredicts expected changes for “heavier” vehicles with increasing forward speed. Further investigation is warranted to quantify the quoted qualifiers. Note also that the analytical results obtained in Figure 7 that indicates a linear increase in $\Delta C_T/C_T^*$ from 0 to 0.4 over the $\mu \in [0,0.3]$ range that does not accurately capture the vortex interaction effects evident in Figure 21. Additionally, inclusion of coupled airframe-rotor flight dynamics produces changes in thrust magnitude that are lower than those from prior work and shown in Figure 4, indicating that airframe dynamics have a damping effect in the presence of disturbances.

Rotor flapping responses (absolute values) are plotted in Figure 22, along with the reference trim values, and the following observations can be made:

- Coning (β_0): the response for the lighter aircraft (denoted by red markers) for both frozen and distorting fidelity levels remain close to each other for $\mu \leq 0.1$, where the largest changes of approximately 1° are noted. Beyond this forward speed, coning response increases when the disturbance is modeled as a frozen field and decreases when the disturbance is modeled as a distorting field. In both cases, the response to the disturbance remains close to trim values. A similar trend is with the heavier aircraft model, with the primary difference being higher trim coning values.
- Longitudinal disk tilt β_c : longitudinal disk tilt is considered positive for a nose up tilting of the disk. For both UH-60 models considered, a greater change in longitudinal disk tilt is obtained using one-way coupling of the disturbance field. The small changes in response with the distorting disturbance relative to trim is attributed to the fact that the strengths of the Lagrangian vortex particles are weak relative to the main rotor wake and aircraft forward speed and thus their influence is minimal in comparison.
- Lateral disk tilt β_s : lateral disk tilt is considered positive for a rightward tilt of the disk when the aircraft is viewed from the back. The lateral disk tilt responses follow similar patterns to those the longitudinal disk tilt responses, with greatest changes obtained with the frozen field model, while those associated with the distorting field remain close to trim.

It is important to note that, unlike the analytical investigations performed above and those from prior work [7] that considered isolated rotors, aircraft dynamics influence the trends noted in Figure 21 and Figure 22. In prior work, the isolated rotors were effectively in straight edge-wise flight with rotor shaft perpendicular to the vortex. Here, the aircraft shaft is not perpendicular to the incoming disturbance and freestream given the aircraft roll and pitch states, built-in rotor shaft tilt, blade hinge offset and blade precone. The aircraft roll and pitch attitudes at trim are shown in Figure 23 for reference.

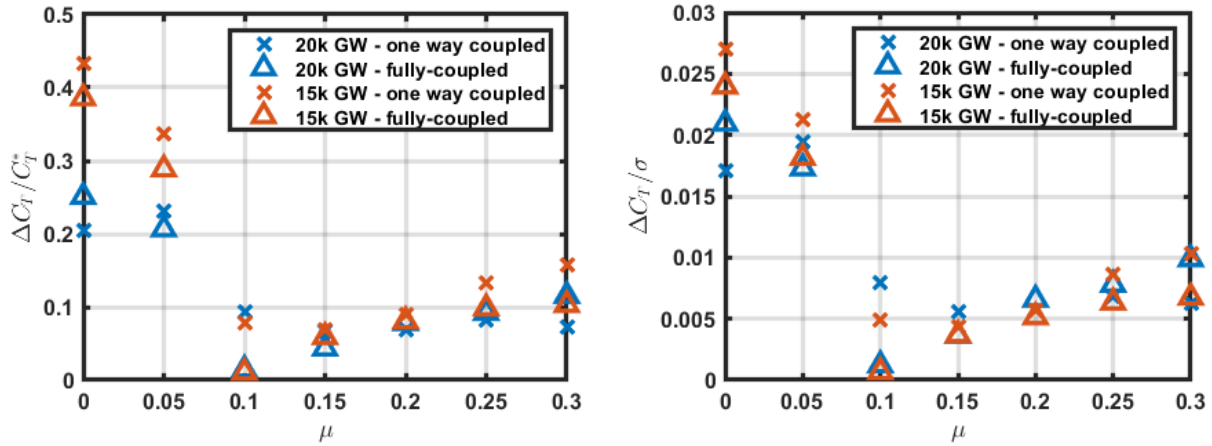


Figure 21: Change in rotor thrust due to isolated vortex influence: as a fraction of thrust at trim (left) and in terms of nondimensional blade loading (right); $\Delta C_T = C_T - C_T^*$, where C_T^* is thrust at trim, and σ is blade solidity.

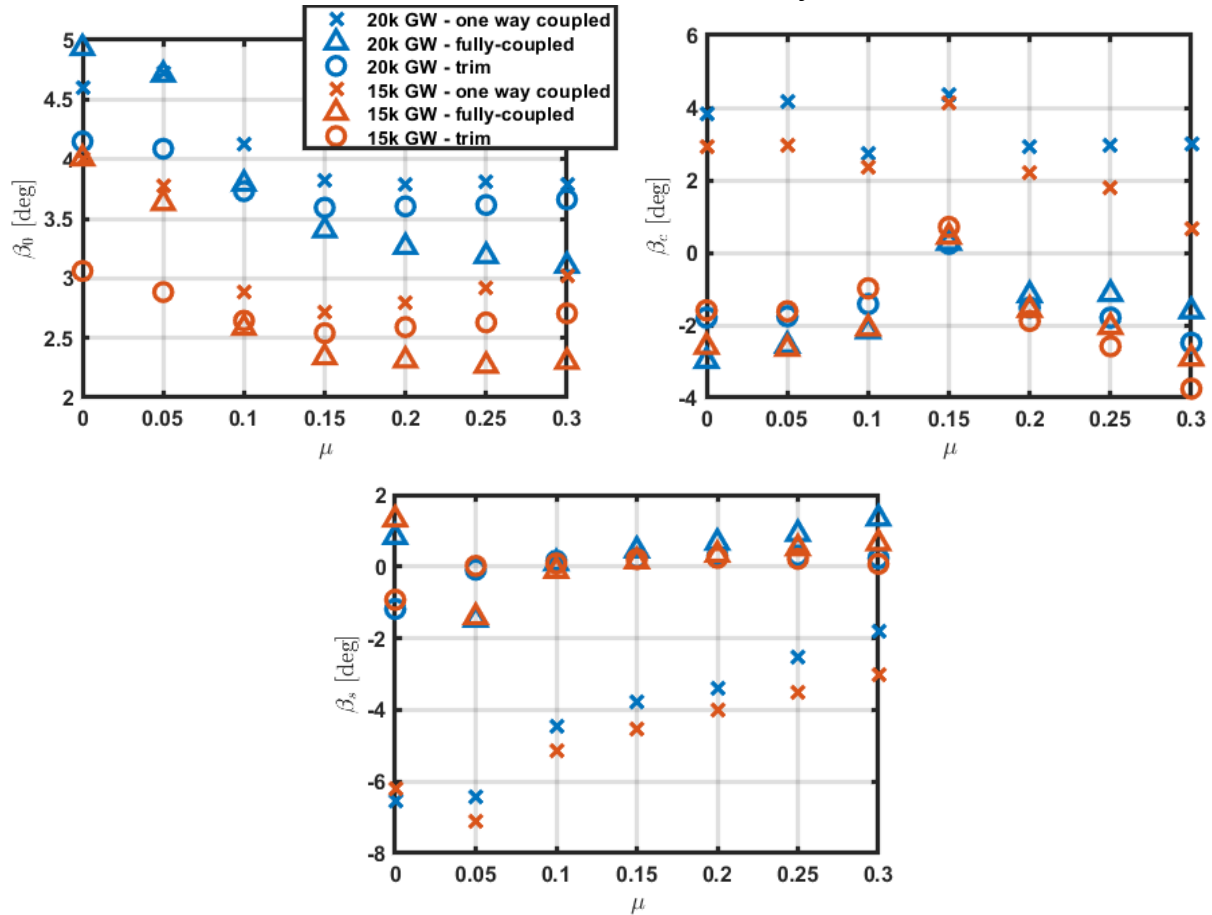


Figure 22: Main rotor disk response to isolated vortex; coning (top left), longitudinal disk tilt, positive nose up (top right) and lateral disk tilt (bottom) positive towards the right be vehicle viewed from the rear.

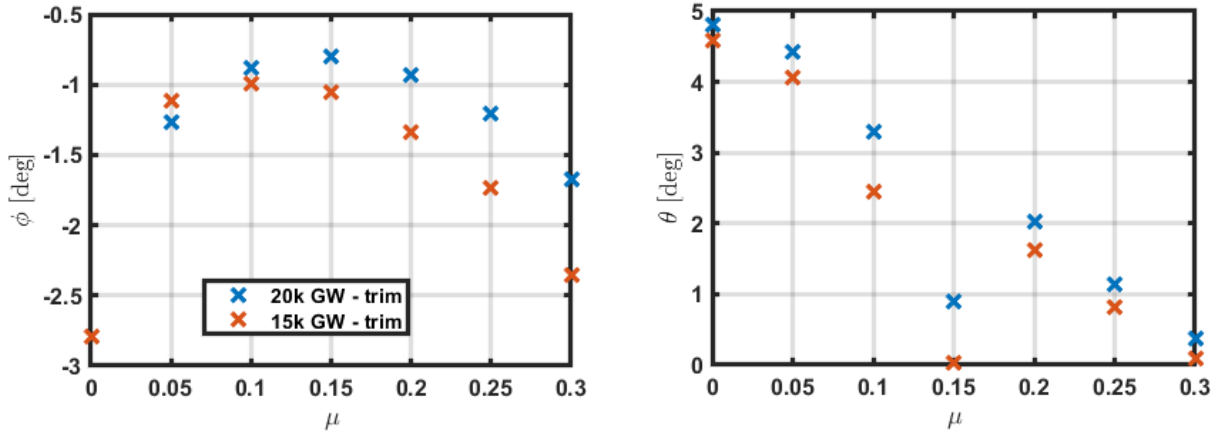


Figure 23: Aircraft roll (left) and pitch (right) trim states at various forward speeds.

Aircraft Response to Simplified Representation of Ship Airwake

We had previously used the arch/horseshoe vortex representation of ship airwake disturbance together with the analytical model given by Eq. (1) to investigate the influence of ship geometry and rotor vertical position variation on fundamental rotor response. This initial investigation indicated the potential viability of disturbance inflow λ^* and blade loading $\Delta C_T/\sigma$ as scaling parameters that can provide insights into rotorcraft responses in dynamic interface scenarios. In this section, we will use the ExHel model and CASTLE/CHARM coupling to further assess the viability of these scaling parameters. Unlike the analytical investigation, here we consider full aircraft dynamic simulations for two levels of disturbance coupling: one-way coupled and fully-coupled interactions. The aircraft is again assumed to be in hover with the rotor placed in line with the disturbance, which is read in via airwake data files as perturbations to the freestream, set to a 30-knot headwind. The ExHel model is first trimmed without disturbance. Time-marching simulations are then performed with the disturbance module turned on. To isolate the aircraft fundamental response, its position is held fixed during this time-marching simulation. We record thirty second time-histories of the responses and use time-averaged values in the results that will be presented below. To examine the influence of aircraft size, we consider two gross weight values: 15,000 lbs. and 20,000 lbs.

Effect of Varying Ship Beam

The effect of varying ship beam on main rotor response is plotted in Figure 24. We note a similar trend in the responses for both gross weights and fidelity levels. This trend matches that observed in the analytical investigation in Figure 16. Additionally, peak response is again noted when the ship beam $W \in [1,2]R$. From Figure 24, λ^* values for the fully coupled cases remain consistently less than those from the one-way coupled cases by approximately 0.001 for both gross weight values when $W > 1R$. For $W < 1R$, the opposite is true. It is interesting to note the difference in magnitude between the responses in Figure 24 and those from the analytical counterparts in Figure 16, where the latter have greater magnitudes. Offsets are evident in Figure 24 in the responses for both gross weights, pointing again to the existence of an additional scaling factor that can potentially “collapse” all the responses onto each other. These offsets are also present with blade loading, see Figure 25. Note that the fully-coupled/distorting wake representation of the horseshoe vortex is *not* equivalent to unsteady and alternating flow structure (similar to the von Karman-streak) present aft of superstructures. Here, the vortex particles associated with the steady representation of the horseshoe vortex are transported due to

the combined effects of freestream, self-induced velocities, velocities induced by other particles, and rotor wake interactions.

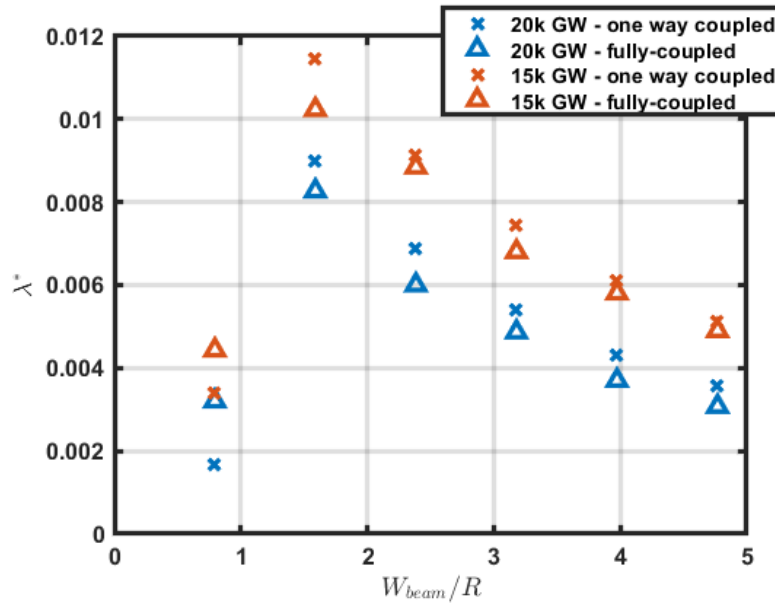


Figure 24: Influence of ship beam variation on CASTLE / CHARM ExHel main rotor inflow; $\lambda^* = \Delta C_T / \sqrt{2C_T^*}$, where C_T^* is the trim thrust coefficient, $\Delta C_T = C_T - C_T^*$.

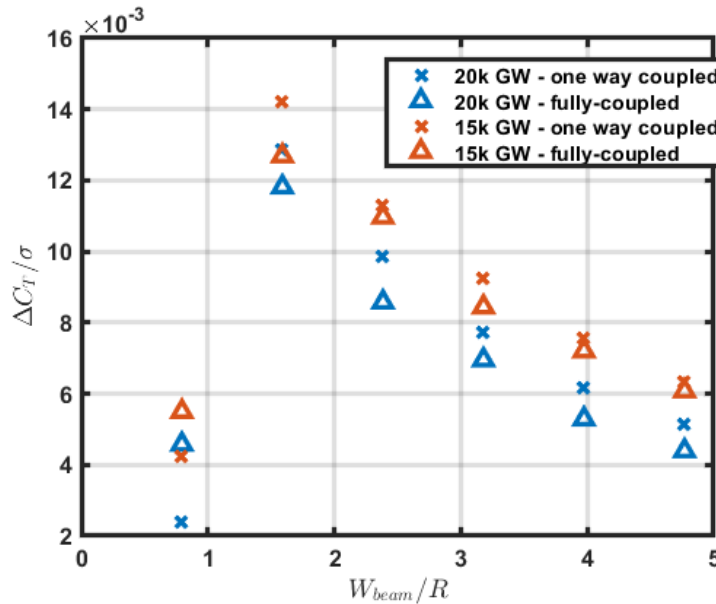


Figure 25: Influence of ship beam variation on CASTLE / CHARM ExHel main rotor blade loading; $\Delta C_T = C_T - C_T^*$, where C_T^* is the trim thrust coefficient and σ is the main rotor solidity.

Effect of Varying Aircraft Height

Next, we investigate the effect of varying rotor height relative to the horseshoe vortex centers. In Figure 17, we had noted an inverse parabolic trend in the thrust coefficient response, with a peak blade loading $\Delta C_T/\sigma = 0.0158$ when the rotor hub center is in the same plane as the vortex centers. Corresponding results for rotor height variation with the ExHel coupled airframe-rotor dynamic model is shown in Figure 26 for hover. Results for both gross weights considered

again follow an inverse parabolic trend. However, this time, peak response is obtained when the rotor is below the vortex plane centers. Modeling the disturbance using the frozen field assumption resulting in conservative blade changes at all height, except for $\Delta y = -0.5$ and $\Delta y = -0.25$, where the responses coincide with those from the distorting fidelity level. Offsets between the nondimensional blade loading responses of both UH-60 models are present at all heights tested, indicating the potential existence of an additional scaling factor that would cause all the responses to “collapse” onto each other. From the figure, we again note responses of lower magnitudes than those obtained with the isolated rotor analytical investigations.

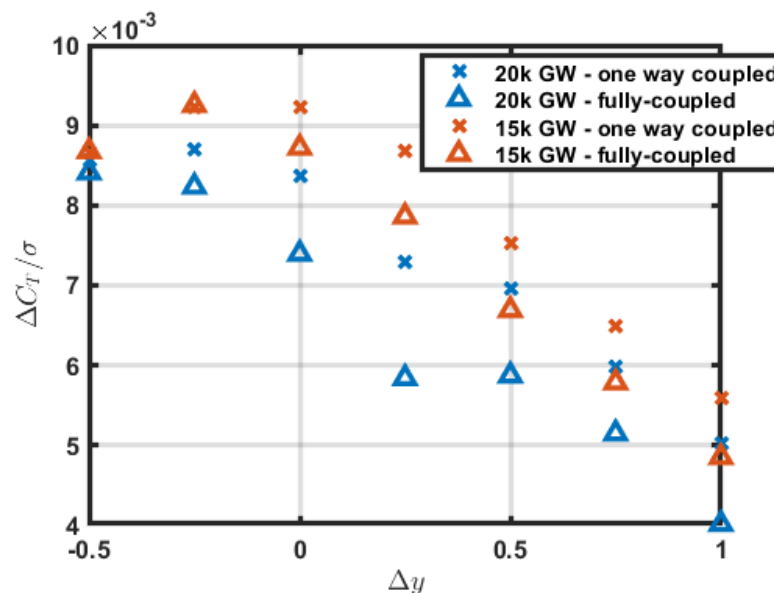


Figure 26: Influence of rotor height variation in the presence of the horseshoe vortex on CASTLE / CHARM ExHel main rotor blade loading; $\Delta C_T = C_T - C_T^*$, where C_T^* is the trim thrust coefficient and σ is the main rotor solidity.

Conclusions

Flight simulation has long been recognized as a valuable tool for gaining insights into the complex ship-rotorcraft dynamic interface, where highly unsteady ship airwake from a moving ship structure interacts with the aircraft and increases pilot workload. A fundamental understanding of what is “good enough” when selecting modeling fidelity for use in such simulations is currently missing. This effort aimed at investigating both ship airwake and rotorcraft response from a fundamental physics perspective to derive scalable parameters and observations that can provide initial insights into dynamic interface of any given ship-rotorcraft dynamic interface without having to rely on expensive configuration-specific simulations. We approached the problem by first focusing on ship airwake characterization, employing two approaches. In one methodology, two dimensional analytical models were fitted onto the CFD predicted flow features to capture the associated longitudinal and vertical velocity profiles. Two-dimensional models were chosen as starting point for simplicity and because they provide a basis for a fundamental, “ground-up” approach to parametric airwake reconstruction. The model input parameters also provide some insight into physical phenomena and can be nondimensionalized and applied to other rectangular obstacles. In the second methodology, we characterized 3D flow features directly as vortical structures in terms of geometry (position, size) and strength. Fundamental rotorcraft responses to simplistic disturbance representations were subsequently

examined. We considered various rotor modeling fidelity levels ranging from isolated analytical rotor response investigations to full aircraft dynamic simulations where representative vortical disturbance structures were modeled as a frozen field with the disturbances fixed in space (also dubbed “one-way coupling”) and as a distorting field (“full coupling”) modeled by solving the Lagrangian vorticity-velocity form incompressible Navier-Stokes equations. We considered responses to two primary vortical structures: an isolated vortical tube representative of the trailing wake from a fixed-wing aircraft and a horseshoe vortex derived from the ship airwake characterization investigation.

In summary, the primary conclusions of the effort were:

1. The parametric model fitting approach to airwake characterization provides an avenue for fast and representative reconstruction of time-averaged velocities associated with flow over rectangular obstacles while providing insights into flow phenomena such as recirculation regions. In this work, we derived analytical parametric expressions for time-averaged longitudinal and vertical velocity profiles and demonstrated their applicability to flow over a rectangular geometry that was not considered in the derivation of the parametric relations.
2. The vortex-based characterization of airwake provides a physical basis for scalable representation of potent vortical structures that directly impact rotorcraft flying qualities based on ship geometry and freestream. We characterized the arch vortex typically observed aft of rectangular obstacles in headwind conditions. We also identified and characterized a horseshoe vortex that allowed for representative reconstruction of vertical velocity, which directly influences rotor inflow, downstream of the obstacle using the Biot-Savart law combined with the Vatistas core model. We demonstrated the applicability of this arch/horseshoe characterization, which was obtained using a headwind simulation of flow over a cube, to flow over a generic ship geometry derived using publicly available ship geometry data.
3. The time-averaged airwake characterization from the two methods we considered can be combined with unsteady predictions from a stochastic model such as the von Karman or Dryden turbulence model to obtain representative time-dependent airwake data. For unsteadiness, the nondimensional vortex shedding frequency or the Strouhal number is an important scaling parameter. We investigated the use of a simple Fourier representation of the unsteadiness along with a multi-bin proper orthogonal decomposition representation of fluctuating velocity components during the effort.
4. For all disturbances considered, inclusion of full aircraft dynamics has a damping effect on rotor thrust and flapping responses when compared to isolated analytical predictions. This can be partly attributed to the trim state of the aircraft, which, unlike the isolated rotor analytical investigations, introduces additional disk tilts relative to the center line of the idealized disturbances.
5. Rotor responses to the simplistic disturbances point towards the existence of scaling parameters that can “collapse” responses of different rotors onto each other. We identified blade loading $\Delta C_T/\sigma$ and disturbance inflow λ^* as two such parameters, although results from the isolated rotor analytical investigations and especially those employing full aircraft dynamic models indicate the need for an additional scaling of these parameters.
6. For a rotorcraft operating aft of ship with a superstructure spanning the beam (e.g. a DDG class ship), peak rotor response is obtained when the ship beam $W \cong 1.3R$, where R is

the rotor radius. We reached this conclusion based on results obtained using the simplified horseshoe vortex characterization of ship airwake for various ship beam values with the rotor/aircraft in hover.

7. For “lighter” aircraft, modeling disturbances as a frozen field provides a conservative estimate of changes in rotor thrust but underpredicts expected changes for “heavier” aircraft with increasing forward speed.

References

1. Smith, M.J., A. Jones, A. Grubb, and J. Lefebvre. *Identification and Quantification of the Role of Turbulence in Aircraft/Ship Aerodynamics*. ONR Annual Review. 2020. Arlington, VA.
2. Silva, M.J., D.A. Wachspress, D.P. Gaublumme, E.W. Hayden, T.S. Davis, and T. Fean. *The Role of Modeling & Simulation in the Mitigation of V-22 Tiltrotor Formation Flight Wake-Induced Roll-off*. 72nd Annual Forum of the American Helicopter Society. 2016. West Palm Beach, FL.
3. Whitehouse, G.R. and R.E. Brown. *Modelling a Helicopter Rotor's Response to Encounters with Aircraft Wakes*. in 28th European Rotorcraft Forum. 2002. Bristol, UK.
4. Whitehouse, G.R. and R.E. Brown. *Helicopter Rotor Response to Wake Encounters in Ground Effect*. in 59th Annual Forum of the American Helicopter Society. 2003. Phoenix, AZ.
5. Whitehouse, G.R. and R.E. Brown, *Modelling the Mutual Distortions of Interacting Helicopter and Aircraft Wakes*. Journal of Aircraft, 2003. **Vol. 40**(No. 3): p. pp. 440-449.
6. Whitehouse, G.R. and R.E. Brown, *Modelling a Helicopter Rotor's Response to Wake Encounters*. The Aeronautical Journal, 2004. **Vol. 108**(No. 1079): p. pp. 15-26.
7. Whitehouse, G.R., *Helicopter Response to Vortex Encounters in the Near-Airfield Environment*, 2003, PhD Thesis, Department of Aeronautics Imperial College London.
8. ADS-33E-PRF. *Aeronautical Design Standard Performance Specification Handling Qualities Requirements for Military Rotorcraft*. in US Army Aviation and Missile Command, Aviation Engineering Directorate. 2000. Redstone Arsenal, Alabama.
9. Keller, J.D., D.A. Wachspress, and J.C. Hoffler. *Real Time Free Wake and Ship Airwake Model for Rotorcraft Flight Training Applications*. 71st Annual Forum of the American Helicopter Society 2015. Virginia Beach, VA.
10. Keller, J.D., D.A. Wachspress, and J.C. Hoffler. *Pilot Evaluation of a Real-Time Free Wake Model in a Navy Rotorcraft Fleet Trainer*. 73rd Annual Forum of the American Helicopter Society 2017. Fort Worth, TX.
11. Polsky, S.A. *A Computational Study of Unsteady Ship Airwake*. in 40th AIAA Aerospace Sciences Meeting & Exhibit. 2002. Reno, NV: AIAA 2002-1022.
12. Keller, J.D., G.R. Whitehouse, A.H. Boschitsch, J. Nadal, J. Jeffords, and M. Quire. *Computational Fluid Dynamics for Flight Simulator Ship Airwake Modeling*. in Interservice/Industry Training, Simulation, and Education Conference (I/ITSEC) 2007. 2007. Orlando, FL.
13. Padfield, G., *Helicopter Flight Dynamics: The Theory and Application of Flying Qualities and Simulation Modeling*. AIAA Educational Series, ed. J.S. Przemieniecki. 1996.
14. Payne, P.R., *Helicopter Dynamics and Aerodynamics*. 1959, New York: The Macmillan Company.
15. Howlett, J.J., *UH-60A Black Hawk Engineering Simulation Program - Volume I - Mathematical Model*, 1981, NASA-CR-166309.
16. Keller, J.D., D.A. Wachspress, J.C. Hoffler, N.J. Kachman, and J. Nichols. *Application of a Real Time Free Wake Induced Velocity Model in a Naval Rotorcraft Flight Trainer*. in 67th Annual Forum of the American Helicopter Society 2011. Virginia Beach, VA.

17. Forsythe, J.R., C.E. Lynch, S. Polsky, and P.R. Spalart. *Coupled Flight Simulator and CFD Calculations of Ship Airwake using HPCMP CREATE™-AV Kestrel*. 53rd AIAA Aerospace Sciences Meeting. 2015. Kissimmee, FL.: AIAA-2015-0556.
18. Beal, T.R., *Digital simulation of atmospheric turbulence for Dryden and von Karman models*. Journal of Guidance, Control, and Dynamics, 1993. **Vol. 16**(No. 1): p. pp. 132-138.
19. Dreier, M.E., *The Influence of a Trailing Tip Vortex on a Thrusting Rotor*, 1977, Penn. State University.
20. Padfield, G.D. and G.P. Turner, *Helicopter Encounters with Aircraft Vortex Wakes*. The Aeronautical Journal, 2001. **105**(1043): p. pp. 1-8.
21. Leishman, J.G., *Principles of Helicopter Aerodynamics*. 2nd ed. 2006, Cambridge, UK: Cambridge University Press.
22. Johnson, W., *Helicopter Theory*. 1980, Princeton, NJ: Princeton University Press.
23. Padfield, G.D. and G.P. Turner. *Helicopter Encounters with Aircraft Vortex Wakes*. in *25th European Rotorcraft Forum*. 1999. Rome, Italy.
24. Padfield, G.D., B. Manimala, and G.P. Turner. *A Severity Analysis for Rotorcraft Encounters with Vortex Wakes*. in *28th European Rotorcraft Forum*. 2002. Bristol, UK.
25. Turner, G.P., G.D. Padfield, and M. Harris, *Encounters with Aircraft Vortex Wakes: The Impact on Helicopter Handling Qualities*. Journal of Aircraft, 2002. **39**(5): p. pp. 839-849.
26. Wachspress, D.A., T.R. Quackenbush, and J.D. Keller. *Rotor Wake Evolution and Vortex Wake Encounter Analysis Methods for Terminal Area Operations*. in *AHS 58th Annual Forum*. 2002. Montreal, Canada.
27. Bilanin, A.J., M.E. Teske, and G.G. Williamson, *Vortex Interactions and Decay in Aircraft Wakes*. AIAA Journal, 1977. **15**(2): p. pp. 250-260.
28. Bilanin, A.J., M.E. Teske, and J.E. Hirsh, *Neutral Atmospheric Effects on the Dissipation of Aircraft Vortex Wakes*. AIAA Journal, 1978. **16**(9): p. 956-961.
29. Teske, M.E., T.R. Quackenbush, A.J. Bilanin, and D.A. Wachspress. *Vortex Roll-up Merging and Decay with the UNIWAKE Computer Program*. in *Aircraft Wake Vortices Conference*. 1991. Washington, D.C.
30. Quackenbush, T.R., M.E. Teske, and A.J. Bilanin. *Computation of Wake/Exhaust Mixing Downstream of Advanced Transport Aircraft*. in *AIAA 24th Fluid Dynamics Conference*. 1993. Orlando, FL: AIAA-1993-2944.
31. Quackenbush, T.R., M.E. Teske, and A.J. Bilanin. *Dynamics of Exhaust Plume Entrainment in Aircraft Vortex Wakes*. in *34th Aerospace Sciences Meeting & Exhibit*. 1996. Reno, NV: AIAA-1996-0747.
32. Teske, M.E., T.R. Quackenbush, A.J. Bilanin, and R.I. Sykes. *Long-Time Aircraft Vortex Wake Predictions and Plume Evolution Consequences*. in *28th AIAA Fluid Dynamics Conference*. 1997. Snowmass, CO: AIAA-1997-1843
33. McKillip Jr., R.M., D.A. Wachspress, J.D. Keller, G.R. Whitehouse, T.R. Quackenbush, and A.H. Boschitsch. *Distributed Multi-Vehicle Simulation Including High-Order Airwake Representation*. 60th Annual Forum of the American Helicopter Society 2004. Baltimore, MD.
34. Whitehouse, G.R., A.H. Boschitsch, and J.D. Keller. *Development and Testing of a Lagrangian-Eulerian CFD Analysis for Moving Body and Interactional Aerodynamics Analysis*. 2019 AIAA SciTech Forum. 2019. San Diego, CA: AIAA-2019-2117.

35. Whitehouse, G.R., A.H. Boschitsch, J.D. Keller, and D.A. Wachspress, *Next Generation of Fast Moderate Fidelity Methods for Interactional Aerodynamics*, 2018, Continuum Dynamics, Inc. CDI-TR-18-4: Final Report under ONR contract N00014-14-C-0014.
36. Heffley, R.K. *A Model for Manual Decelerating Approaches to Hover*. 15th Annual Conference on Manual Control. 1979. AFFDL-TR-79-3134.
37. Wachspress, D.A., T.R. Quackenbush, and A.H. Boschitsch, *Rotorcraft Interactional Aerodynamics with Fast Vortex/Fast Panel Methods*. Journal of the American Helicopter Society, 2003. **Vol. 48**(No. 4).
38. Wachspress, D.A., T.R. Quackenbush, and A.H. Boschitsch. *First-Principles, Free-Vortex Wake Model for Helicopters and Tiltrotors*. 59th Annual Forum of the American Helicopter Society. 2003. Phoenix, AZ.
39. Pitt, D.M. and D.A. Peters, *Theoretical Prediction of Dynamic Inflow Derivatives*. Vertica, 1981. **Vol. 5**(No. 1): p. pp. 21-34.
40. Peters, D.A. and N. HaQuang, *Dynamic Inflow for Practical Applications*. Journal of the American Helicopter Society, 1988. **Vol. 33**(No. 4): p. pp. 64-68.