

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

FY 2023 Report

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Under Contract No. N00014-21-C-1044



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August 17, 2023

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.

The effort, which commenced in March 2021 is undertaking the research required to develop such an understanding, along with disseminating the observations and conclusions of the work to the Navy and the broader flight dynamics and handling qualities community. The effort is structured using a build-up approach that first focuses on defining relevant disturbance fields, followed by predicting and understanding the fundamental aeromechanics response (e.g. aerodynamic forces and moments and rotor dynamics), and will culminate in predicting the flight dynamics and flying qualities for realistic, but generic, helicopter and tiltrotor configurations. To date, the effort has focused on investigating the type of disturbance fields experienced by Naval aviators, and how to define the relevant primary flow structures and time scales.

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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].

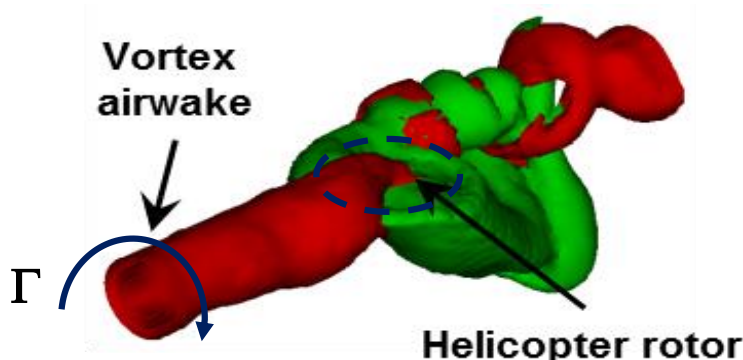


Figure 2: Predictions of interacting rotor wake (green) and airwake (red) with direction of rotation of the vortex and the location of the rotor disk in blue

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.

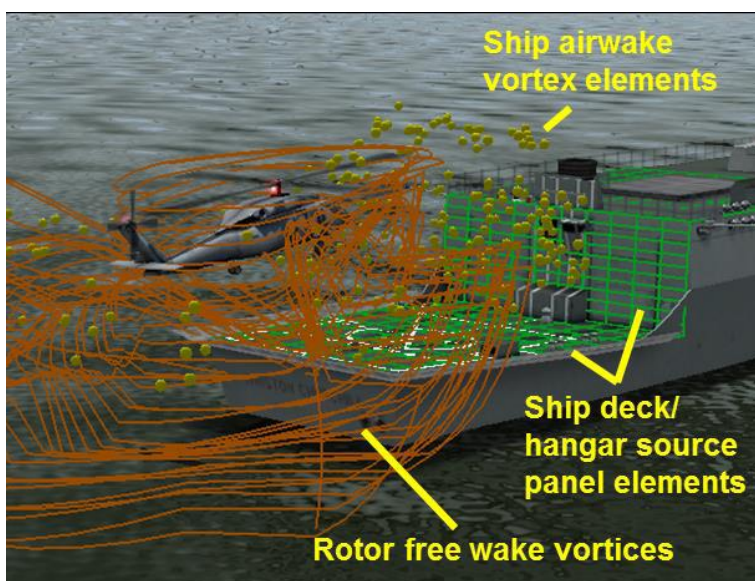


Figure 3: CASTLE / ExHel / CHARM visualization of shipboard operations

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

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.

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 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.

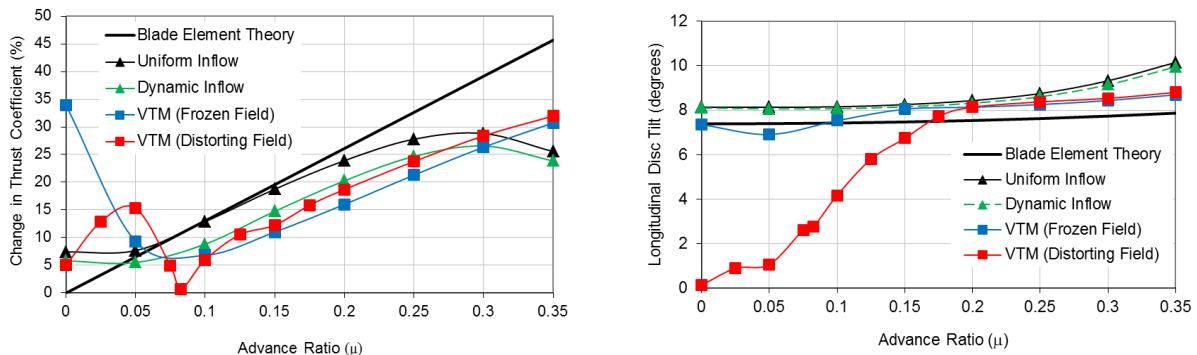


Figure 4: Mean perturbations to rotor thrust and longitudinal disc tilt for an isolated rotor interacting with a vortex aligned with the flight path. Adapted from [6, 7]

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.

Task Overview

Definition of Disturbance Field Fluid Dynamics Scales Relevant to Naval Rotorcraft Operations

The temporal and spatial fluid dynamics scales associated with disturbance fields experienced by Naval aviators during both land-based and shipboard operations will be quantified. Characteristic properties will be determined in order to assist in the development of synthetic “surrogate” disturbance fields. The following discussion presents an overview of the types of flow structures present in a ship airwake that this task will seek to characterize and task 3 will represent.

It is well known that the ship airwakes contain a wide spectrum of spatial and temporal scales, with structures as large as the beam of the ship all the way down to very fine scale high frequency turbulent structures (see Figure 5). Far downwind of the ship, the airwake is composed of relatively weak chaotic structures associated with the turbulent breakdown of the vortical structures as they age. Near to the ship, and most notably for DI operations, near to landing spots, the flow can be critically different.

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)

The flow near to and over the hangar of a small-deck ship is dominated by the roll-up and shedding of a strong horseshoe-like vortical structure from the sides and roof of the hangar [36]. The induced flow over the deck causes the boundary layer near to the stern to roll-up into a pair of counter-rotating vortices aligned with the flow [36, 37]. A pressure difference between the sides and top of the ship can cause the flow around the bow of the ship to form a “wing vortex” like structure that wraps around the fore of the ship and becomes aligned with the flow downstream along the sides of the ship. In some cases, these vortices can be entrained into the flow-aligned pair of counter-rotating vortices trailed from the ship deck.

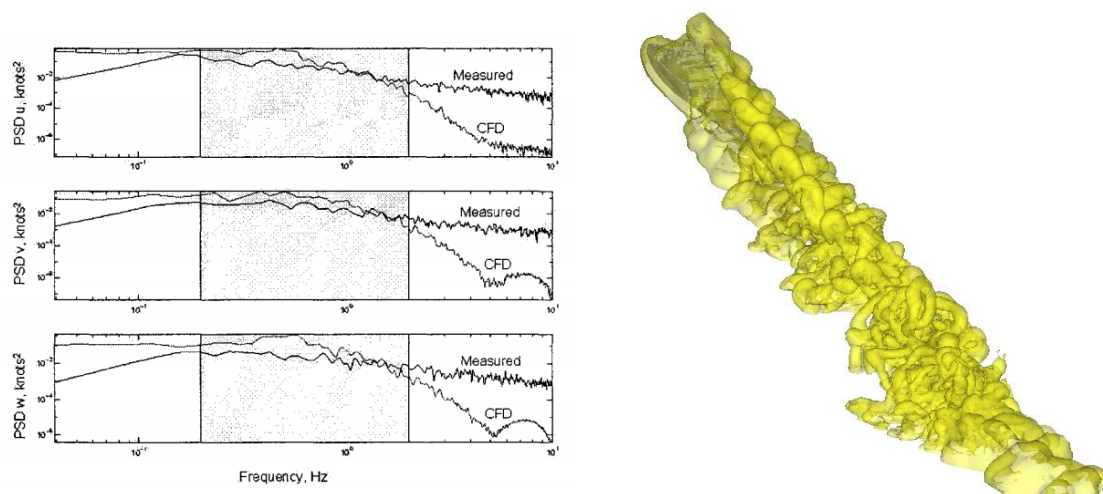


Figure 5: PSD of measured and computed velocity spectra for a ship airwake from [38] (left) and CDI CFD prediction of the wake behind a LPD-4 from [39]

The flow around flat-topped ships, such as aircraft carriers and amphibious assault ships, includes regions behind the superstructure that are grossly similar to those just described for small-deck ships, but also include “wing vortex” like structures trailed from the upstream deck edges. At zero wind over deck, the flow wraps up and over the leading edge of the deck forming a large separation bubble that periodically sheds vortical structures. Around the deck edge, and deck notches in the case of a carrier, wind-aligned “wing vortices” are trailed downstream. At non-zero wind over deck, the leading edge separation bubble is greatly diminished, though the “wing vortices” become more pronounced and can trail across the deck (and landing spots).

It should be noted, that the descriptions of the flow just given present a time-averaged perspective, and the actual flow field is highly unsteady with many of the afore-mentioned flow structures being shed from the deck at frequencies related to the flow speed and the characteristic dimension of the shedding structure (i.e. the ship’s beam, hangar height etc.). “Wing vortex” like structures, such as those trailed from the edge of a flat-top ship along the deck, are likely to be more stable given the tight, concentrated vortical structure.

Generation of Synthetic Disturbance Fields

A set of representative “synthetic” disturbance fields will be created. To aid in undertaking a systematic variation of the flow field in order to decompose the fundamental aeromechanics, FD and FQ responses, these fields could be as simple as a single (“wing” or “deck edge”) vortex, a set of vortices, or as sophisticated as a generic turbulent field with given statistical properties (i.e. atmospheric turbulence) or a CFD-generated ship airwake. It is anticipated that the numerical representations of the disturbances will be formulated as both velocity fields and distorting

vorticity fields compatible with the basic FD model, as well as CHARM Lagrangian and VTM2 grid based representations of the simulation model described below. Full 4D representations will be developed for the appropriate length of time. Solutions will be initialized with the full 3D disturbance field, and advanced by using the field as an upstream boundary condition. In the CHARM-based model (see discussion below), the field will be represented as vortex particles and will evolve according to the Lagrangian form of the vorticity transport equations as in [9, 10]. In the VTM2-based model [34, 35], the flow field will be represented on a 3D grid and will evolve according to the Eulerian form of the vorticity transport equations as in [3-7] (Figure 2), albeit now on an adaptive grid.

In many DI simulations the resolution of ship airwake disturbance fields focuses on the frequency range most associated with pilot workload (see shaded region on Figure 5 left), which is typically 1-10rad/s (0.2-2Hz). This is the frequency range at which pilots typically close the loop around the aircraft/flight control system, though there may be certain circumstances, like station keeping, where a pilot may be able to respond faster. Below this range, the response does not impact workload, and manifests as an essentially steady input. Providing loop closure at higher frequency is not physiologically possible, though such high frequency content will manifest as vibrations transmitted to the fuselage and thus ride quality.⁵ In this effort, we seek to distinguish between the fundamental aeromechanics response of the rotor system, the aircraft and what the pilot can respond to; thus we will not filter any of the “synthetic” disturbance fields.

Definition of Aeromechanics and HQ Metrics

This task will see the definition of aeromechanics performance and FQ metrics along with a detailed simulation test matrix. Emphasis will be on establishing appropriate and reproducible metrics with which to evaluate the influence of a disturbance field on the aircraft’s force and moment response (Year 2) and FD and FQ (Year 3). Both can be related back to the ADS-33 design standard, though subjectiveness introduced by the pilot ratings, and indeed nuances associated with aircraft specific control systems and stability augmentation systems, can be difficult to isolate. The approach considered here is to rely upon the fundamental performance metrics, as in prior work in the context of multiple aircraft interactions [20, 23-25, 33], where the aircraft is trimmed and then the controls are held fixed. The resultant response is compared directly to the design standard specifications to quantify the severity of the response and the ability of the aircraft to reject the disturbance. Given the complexity of modern aircraft control systems and the role of the pilot, careful attention must be made to distinguish between fundamental aircraft performance (response) and subjective metrics that are aircraft and/or pilot specific.

One could develop single/multi-axis controllers that would function as a regulation/tracking “pilot” to adjust the controls to maintain a given maneuver, though while the control variation required to reject the disturbance could be compared to the design standards, this approach is a better test of the controller than of FD and FQ. Similarly, development of a formal pilot model with appropriate gains and crossovers to mimic a real-world pilot would require extensive validation and would still only produce subjective assessments.

In the analysis to be undertaken in the second year of the effort, only the aircraft’s fundamental response (aerodynamic forces and moments along with rotor dynamic response)

⁵ Loads in flap are transmitted to the fuselage a multiples of N/rev (i.e. N/rev, 2N/rev, 3N/rev etc.), where N is the number of blades. Chordwise loads, that couple with the fuselage body modes, are transmitted at multiples of $N\pm 1/\text{rev}$ (i.e. $(N\pm 1)/\text{rev}$, $(2N\pm 1)/\text{rev}$, $(3N\pm 1)/\text{rev}$ etc.).

will be investigated to look at pure aeronautics without the complications of aircraft specific properties such as stability augmentation etc. since ultimately, it is the fundamental response that drives the aircraft's FD. In the third year of the effort, a more sophisticated engineering model will be developed to represent specific aircraft characteristics, such as cross-couplings between propulsion system and the rotor, as well as control systems. With this model in hand, the work undertaken in year 2 will be extended to include flying qualities.

Generic FD Model Assembly

In conjunction with the development of aeromechanics, FD and FQ metrics, the FD model for undertaking the simulations will be assembled and tested. Component system models will be validated as they are developed. For example comparing to Carpenter and Fridovich's data [40] for a rotor's response to a ramp collective input would demonstrate that both the rotor dynamics and the unsteady aerodynamic feedback between the impulsively shed wake from the change in collective, are adequately modelled). It is currently anticipated that the simulation will be based around the Navy's CASTLE 6-DOF FD framework (CDI will request permission from NAVAIR for its use in this project) coupled to the CHARM rotor, fuselage and ship airwake model – as in [9, 10] – and the VTM2 model developed under prior ONR sponsorship [34, 35].

This suite of FD models will provide the ability to take a systematic step-wise increase in capability within the same analysis to investigate the role that modeling fidelity plays on FD and HQ during an interaction with an external disturbance field. The anticipated levels of fidelity offered by the model are, in order of increased fidelity,

1. Finite state wake model coupled to a frozen disturbance field
2. Free wake model coupled to a frozen disturbance field
3. CFD wake model coupled to a frozen disturbance field
4. Free wake model coupled to a distorting (particle method) disturbance field
5. CFD wake model coupled to a distorting (CFD) disturbance field

While the VTM2 model, derived from the same model used by Whitehouse and Brown [3-7], and CHARM can be thought of as being comparable from a FD perspective, VTM2 is able to predict more accurately the natural coalescence and rupture of vortical structures in the wake and disturbance field than the hybrid filament-particle method in CHARM.

The test matrix to be investigated will be developed based upon analysis of the literature as well as discussions with ONR and Navy personnel. A limited number of relevant flight conditions will be selected, and the level of modeling fidelity used to represent the wake and the disturbance field will be varied, as above. At the very least, steady level flight, as investigated by Padfield and co-workers [20, 23-25], will be studied as it is convenient for mapping back to the ADS-33 standards; however other conditions, such as a generic approach may be considered.

Fundamental Helicopter Response

The analysis of the response of a conventional helicopter configuration to the series of disturbance fields will commence in the second year of the effort. This task will start with the assembly of a generic helicopter model, possibly based upon the "example helicopter" included with CASTLE, and the level of modeling used to represent the aircraft will be varied. It is currently anticipated that the following list, in order of increasing fidelity, will be considered:

1. Isolated main rotor (no representation of the airframe, and no tail rotor for the conventional helicopter)

2. Main rotor and tail rotor
3. Rotors and fuselage (lookup table)
4. Rotors and fuselage (panel method for the fuselage)

Given the 4 permutations of helicopter model and the 5 permutations of wake/disturbance field modeling to be evaluated for each wake disturbance field and flight condition of interest, the test matrix gets quite large, and thus data analysis will be an extensive part of this task. A detailed breakdown of the influence of each parameter on aeromechanics will be documented, and conclusions about aeromechanics response, the level of modeling fidelity required and ultimately which length and time scales associated with the fluid dynamics of disturbance fields influence aircraft aeromechanics will be made.

Fundamental Tiltrotor Response

This task will commence with the assembly of a suitable tiltrotor model and will culminate with undertaking the same series of investigations described above for a conventional helicopter. It is currently anticipated that significant differences in the aircraft response - most notably in roll - will be observed when compared to the helicopter investigated earlier.

Helicopter Flight Dynamics Response

This task will build upon the conventional helicopter configuration modeling investigated in year 2 to assemble a FD model of a complete aircraft. Specific properties, such as weight, control systems etc., will be selected based upon interactions and possible collaboration with Navy personnel. Once the model has been assembled, the test matrix of cases investigated earlier will be repeated. In addition to predictions and comparisons of the fundamental aerodynamics response, additional FD and FQ metrics will be evaluated. A detailed breakdown of the influence of each parameter on aeromechanics will be documented, and conclusions about flight dynamics, flying qualities, the level of modeling fidelity required and ultimately which length and time scales associated with the fluid dynamics of disturbance fields influence aircraft aeromechanics will be made.

Tiltrotor Flight Dynamics Response

The effort will culminate in the development of a complete FD model of a tiltrotor, complete with control system models and cross-couplings etc⁶, based upon interactions and possible collaboration with Navy personnel. The test matrix evaluated previously will be repeated for the tiltrotor and conclusions about FD/FQ, modeling fidelity and the length and time scales critical to FD/FQ will be made.

⁶Such as the cross-coupling between the throttle command, the engine, transmission and resultant collective in the V-22

Results and Discussion

Work to date has focused on investigating the type of disturbance fields experienced by Naval aviators, and how to define the relevant primary flow structures and time scales. Initial work was summarized in the first annual report and below. Recent work has continued investigations into how to parameterize the wake structures and how to use simpler models to represent them. Flight dynamics model development and quantification of a rotorcraft's fundamental response to interactions with wake structures has commenced.

Simplified Disturbance Model Development

During the past year work continued on developing and testing a method for formulating representative canonical airwakes. An analytical model fitting approach was formulated and performed on various planes for time-averaged longitudinal and vertical velocities obtained from CFD simulations. Model input parameters, and their spatial variation in the various 2D planes considered provide quantitative insights into the primary coherent structures present in the flow, as well as their spatial evolution. Three-dimensional reconstruction of the time-averaged velocity fields was also performed, demonstrating the adequacy of the analytical models in capturing general flow behavior. Modular scripts, that automatically determine model parameters using an error minimization procedure, have been developed and initial results are presented in this report. Additionally, a flow feature characterization approach in terms of geometry and strength was also pursued. Initial results for this characterization along with preliminary results on the influence of flow structures on simplified helicopter rotors of different scales are presented below. A spatiotemporal characterization of flow dynamics using a multi-resolution proper orthogonal decomposition approach was evaluated as well. Results from this characterization supplement those from the time-averaged analyses and provide quantitative assessments of the turbulent kinetic energy associated with each coherent feature and their corresponding frequencies (time scales). The time-averaged and dynamic characterization of flow features collectively represent parametrizable metrics that can be employed to generate a representative airwake in the vicinity of differing ships or obstacles and/or varying freestream velocities, without having to resort to explicit case-specific CFD simulations.

A description of the CFD simulations used for verification is provided next for reference. The flow feature characterization methodology, the analytical modeling approach, the dynamic spatiotemporal characterization, and rotor fundamental responses to a representative flow feature, are then presented.

CFD Simulation (for Verification)

CFD simulations were performed using CDI's CGE/VorTran-M flow solver [12, 41]. CDI's adaptive cut-cell octree Cartesian Grid solver (CGE) is a Cartesian grid solver that solves the compressible URANS equations using either a Spalart-Allmaras (SA) [42] or a shear stress transport (SST) turbulence model and resolves boundary layers and other highly anisotropic flow features in an efficient manner using wall functions. The VorTran-M model simulates the evolution of initial vorticity distributions in unbounded domains. The CGE/VorTran-M coupled arrangement consists of implementing the CGE solution on the grid as an "inner" solver that extends sufficiently far to contain regions with significant compressibility or flow turbulence and VorTran-M as an "outer" solver that is applied in the essentially incompressible flow region and efficiently transports the vorticity with minimal dissipation. Such an arrangement allows for computational savings in mesh resolution when compared to a solely CGE-based simulation.

This coupled setup has been previously used for both ship and urban airwake modeling [12, 41, 43].

Flow feature characterization has focused on headwind flow over a cube, and the primary flow features associated with this configuration are illustrated in Figure 6 and include:

- A horseshoe vortex that forms upstream of the obstacle where the flow stagnates and wraps around the cube (feature “A” on Figure 6);
- Local separation and reattachment regions on the top and sides (“B” and “C” on Figure 6);
- In the lee of the obstacle, an arch vortex (feature “D” on Figure 6) that forms due to the separation of the shear layers from the top and side surfaces. The streamlines aft of the obstacle indicate a recirculation region, where the direction of the flow reverses.

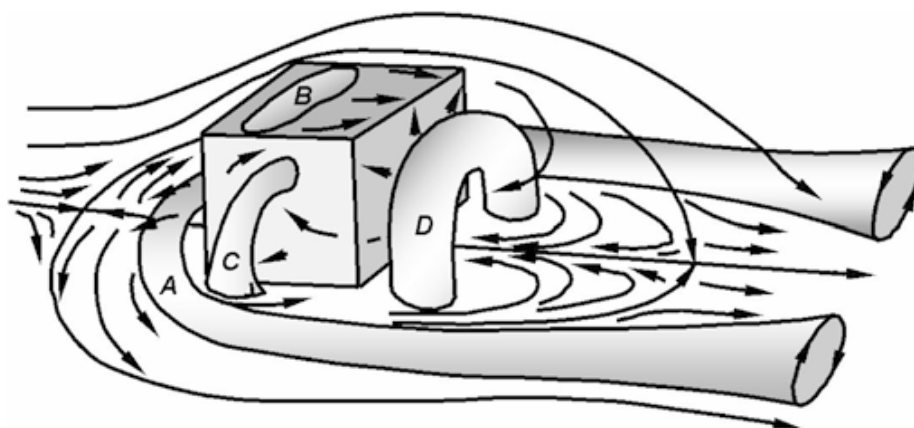


Figure 6: Schematic of principal flow features around surface-mounted obstacle [44].

CFD simulations were performed for a 30 m/s headwind over a 10 m cube. Although this speed is larger than would be typically encountered in practice, it is necessary to use a larger freestream velocity to maintain good numerical conditioning of the compressible flow solver. An alternative approach would have been to take advantage of the preconditioners implemented in CGE for low-speed flows. However, the higher velocity is appropriate given that the flow field is dominated by separation from the sharp edges of the cube, which has a weak dependence on viscosity. This further allowed us to perform simulations for inviscid flow only. Neglecting viscosity effects allows for scaling of time-accurate flow predictions using freestream velocity – see [12] for more details on basis of this modeling approach. Note that no explicit atmospheric boundary layer (ABL) model was included in the simulation.

Simulations were performed using a fixed time step of 0.005s, and a variable number of sub-iterations were used locally to ensure step convergence. Prior to starting the fully unsteady CGE/VorTran-M calculation, a steady-state CGE simulation was carried out for a finite number of iterations to “wash out” any strong starting vortices associated with impulsively starting the transient CGE/VorTran-M solution. This sequence enables an expedient solution that does not require the code to resolve and propagate the starting vortices far downstream, as would otherwise be expected from an impulsive start. For the case considered here, the unsteady simulation was carried out for a total of 40s, where the first 15s were viewed as a transition from steady to transient simulation, and discarded. The subsequent 25 seconds worth of data were recorded for post-processing at 0.1s increments.

The vortex shedding frequency is characterized by the Strouhal number, which is defined as

$$St = \frac{fb}{U} \quad (1)$$

where f is the vortex shedding frequency and b is the characteristic length. Results from the literature indicate dominant periodicity for flow aft of a cube at a distance of $6H$ [45] to have a characteristic frequency of $St = 0.104$ [45, 46], where H is the cube height. Using 10 m cube length as characteristic length and the freestream velocity of 30 m/s as characteristic velocity, this Strouhal number corresponds to a vortex shedding frequency $f = 0.3$ Hz, which, in turn, corresponds to a period of 3.2 seconds. The trimmed 25s simulation duration thus allows for approximately 8 cycles of vortex shedding to be captured. CFD results were compared to results from literature in the previous annual report.

Flow features noted in Figure 6 were identified in our simulations as well, as indicated in Figure 7, where two-dimensional (2D) planes are utilized to highlight the individual flow features. Flow feature characterization was approached using two methodologies. In the first methodology, two dimensional analytical models were fit onto the 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 airwake reconstruction. Additionally, the model input parameters provide some insight into physical phenomena. The planes shown in Figure 7 were used as reference planes for model fitting. The second methodology characterizes 3D flow features directly as vortical structures in terms of geometry (position, size) and strength. All position coordinates in this report, unless stated otherwise, are defined relative to the right-handed coordinate system shown in Figure 7 that has its origin at the center of the bottom face of the cube. Freestream is in the negative z direction.

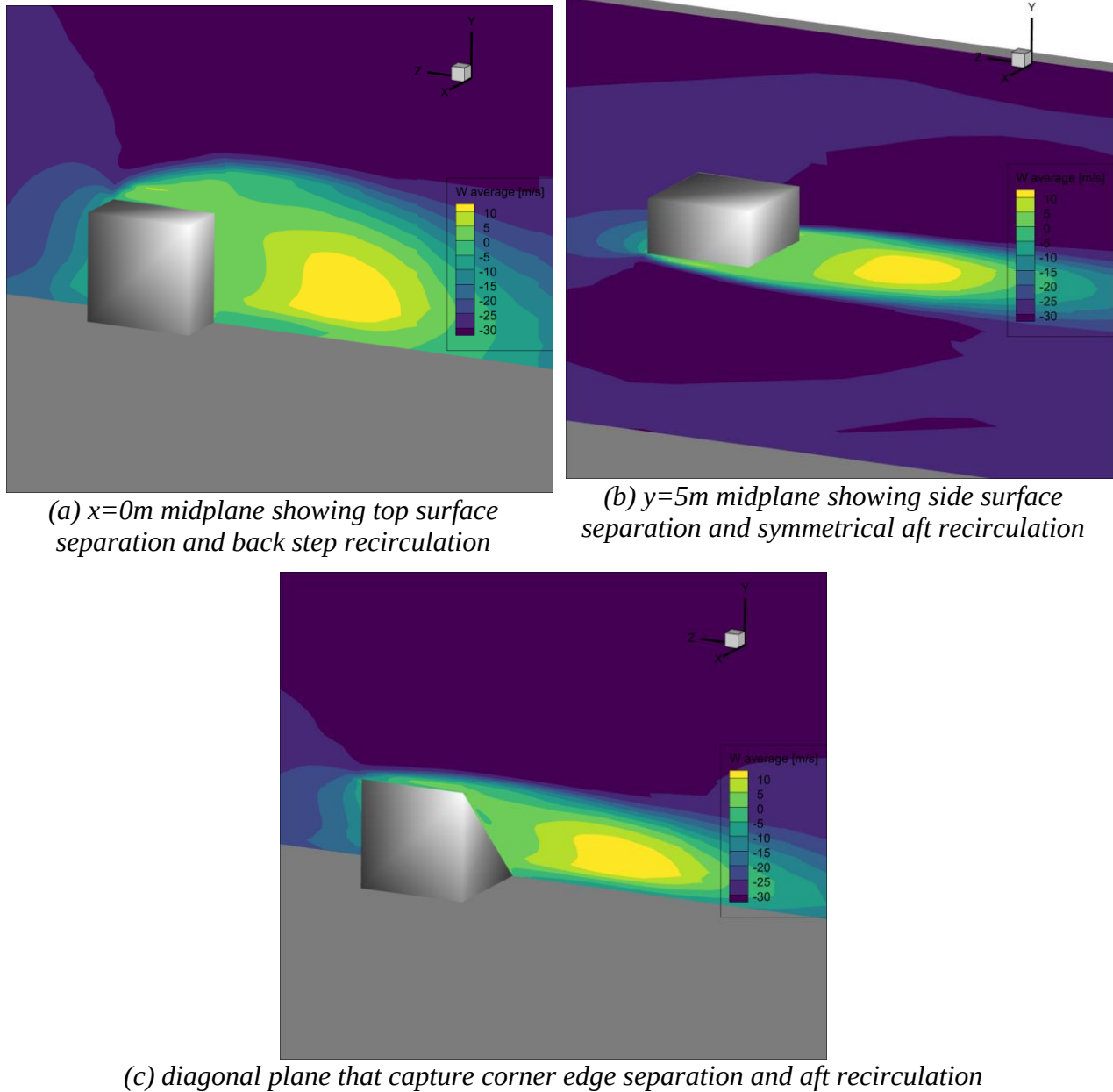


Figure 7: Contour of time-averaged longitudinal velocity for a 30m/s headwind simulation over a 10m cube using CGE/VorTran-M along planes containing primary flow features.

Flow Feature Characterization – Arch Vortex

Flow structures noted in Figure 6 are vortical structures that can be characterized in terms of their *geometry* (position and size) and *strength* (circulation). To start off, geometry and strength characterization was carried out for the arch vortex aft of the surface mounted cube with the goal of deriving an associated induced velocity function $v_{vortex}(r, \psi)$ that could, in turn, be used to estimate the fundamental response of a rotor (see Eq. (17) below). We employ a planar approach to the characterization, where we examine the time-averaged velocity, Q-criterion, and Δ -criterion distributions in various planes to identify

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- a. the center of the arch vortex,
- b. the associated viscous core radius and
- c. corresponding strength.

Definitions for the Q- and Δ -criteria can be found in Ref. [47]. The planes considered consist of the $x = 0\text{m}$ midplane shown in Figure 7(a), and the $y = \{2.5, 3.5, 5, 7, 9\}\text{m}$ planes. Figure 8 shows quiver plots of the velocity field across various $y = \text{constant}$ planes. The figure follows the general CGE/VorTran-M coordinate system described above and plots the velocity field aft of the obstacle. The aft recirculation zone is apparent with the blue “hole” near $z = -20\text{m}$. The arch vortex exists within the “white” region that bounds the hole on the Figure. The process we used in identifying the arch vortex center, size and strength consisted of:

1. Plotting the velocity field in the plane of interest as a quiver plot to locate vortex centers;
2. Ensuring any rotational behavior observed corresponded to a vortex by cross-checking with corresponding Q-criterion and Δ -criterion contour plots;
3. Picking out the vortex center position and the position where maximum tangential velocity is noted (the latter demarks the vortex core limit); and
4. Computing the circulation associated with the region that encloses the vortex.

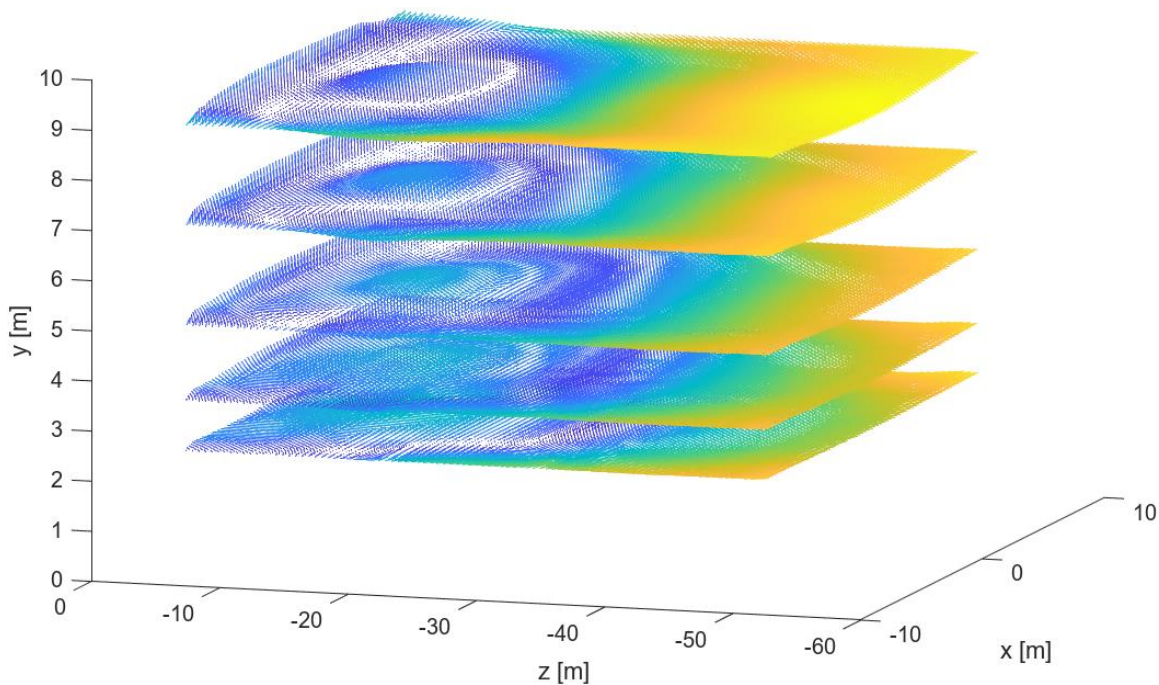


Figure 8: Quiver plot of in-plane velocity components at various heights; left to right along the z axis follows the flow downstream, down to up across the y axis goes upwards from ground.

We illustrate these steps using the $y = 5\text{m}$ plane. The quiver plot for time-averaged in-plane velocities is shown in Figure 9. From the figure, two vortices with centers at $[z, x] = [-15, -6.5]\text{m}$ and $[z, x] = [-17, 6.5]\text{m}$ can be identified. Cross checking with the zoomed in Q- and Δ -criteria plots shown in Figure 10, we note that a vortex does indeed exist at $[z, x] = [-15, -6.5]\text{m}$. A stronger vortex exists near $x \approx -8.0\text{m}$, likely associated with the alternate vortices shed from the vertical edges of the cube. We assume symmetry exists and focus on this one confirmed vortex. It is important to crosscheck the centers identified from the quiver plots

with those in Q- and Δ -criteria plots because, by themselves, quiver plots can fail to identify vortex cores depending on the reference frame relative to which they are plotted [48]. From the quiver plot in Figure 9, peak tangential (x) velocity along the $z=-15\text{m}$ line (where the vortex center was identified) is noted at $x=-0.5\text{m}$, resulting in a vortex core radius size of

$$r_c = |-6.5 - (-0.5)| = 6\text{m}. \quad (2)$$

The final step consists of computing the vortex strength or circulation, which is defined as:

$$\Gamma = \oint_C \mathbf{v} \cdot d\mathbf{l} = \int_S (\nabla \times \mathbf{v}) \cdot d\mathbf{S} = \int_S \boldsymbol{\omega} \cdot d\mathbf{S}, \quad (3)$$

where $\mathbf{v}$ is the velocity field, $d\mathbf{l}$ is an infinitesimal length along a closed circuit C and $\boldsymbol{\omega}$ is the vorticity vector. Note that we apply Stokes theorem in Eq. (3) to convert the line integral to the surface integral. To compute the circulation, we first compute the out of plane vorticity by taking the curl of the planar velocities and then carry out a surface integral over the region bounded within $z \in [-13, -17]\text{m}$ and $x \in [-8.5, -3.5]\text{m}$, a region selected from examining the Q- and Δ -criteria plots in Figure 10. This results in a circulation value of $\Gamma = 33.7 \text{ m}^2/\text{s}$.

We repeated the characterization procedure using various planes in the 3D space. Results are summarized in Table 1. Note that for the $x=0\text{m}$ midplane shown in Figure 7(a), a secondary and more potent vortex exists further downstream at $z=-21\text{m}$, where part of the shear layer flows back into the recirculation zone while the other gets entrained downstream by freestream velocity.

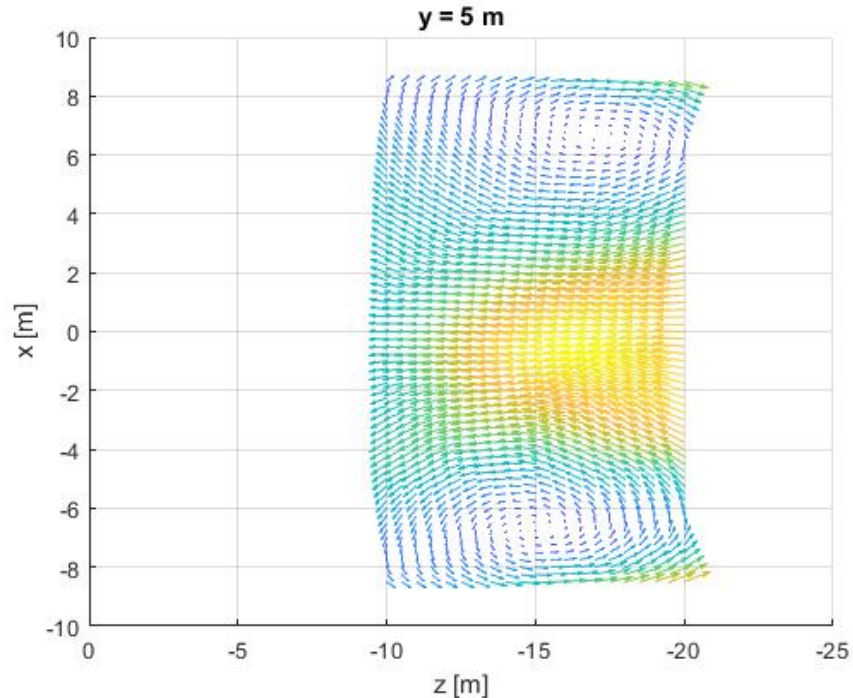


Figure 9: Quiver plot for $y=5\text{m}$ plane.

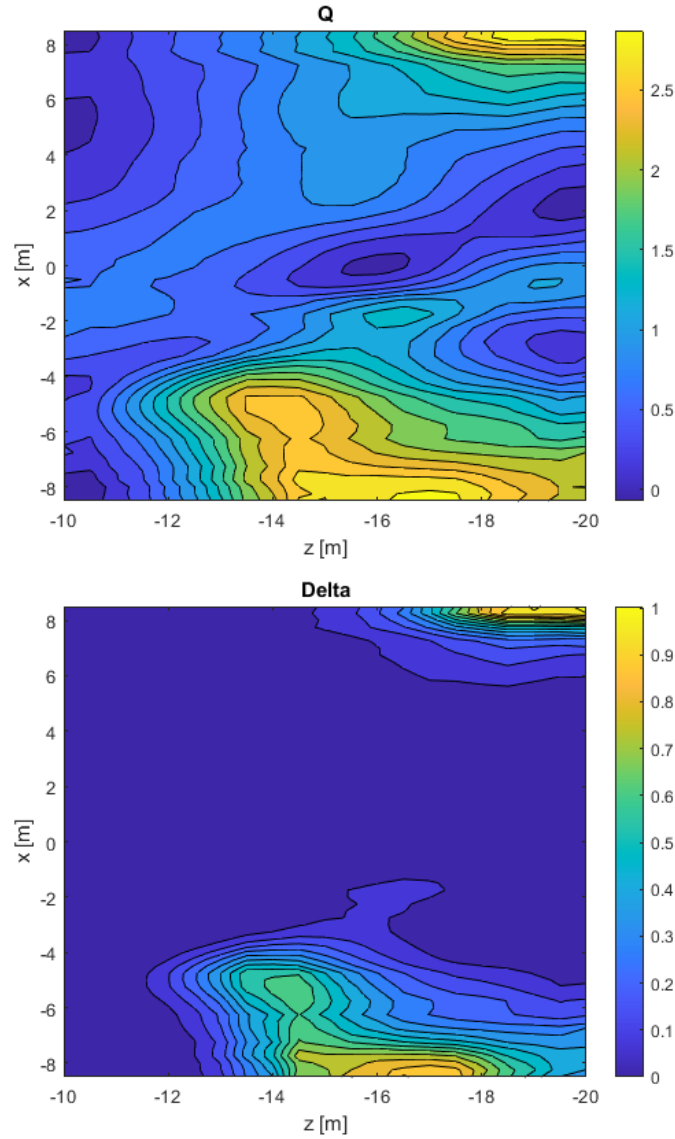


Figure 10: Q -criterion (top) and Δ -criterion (bottom) distributions for $y=5\text{m}$ plane.

Table 1: Arch vortex characterization along different planes.

Plane	Vortex #1 loc [m]	Radius [m]	Circ strength [m ² /s]
x=0m	$[z, y] = [-18, 12]$	1	26.5
y=9m	$[z, x] = [-16, -4.25]$	3.75	33.6
y=7.5m	$[z, x] = [-15, -5.5]$	4.5	33.1
y=5m	$[z, x] = [-15, -6.5]$	6	33.7
y=3.5m	$[z, x] = [-15, -7.5]$	7	31.5
y=2.5m	$[z, x] = [-16.5, -7.75]$	7.25	31.9

The arch vortex information provided in Table 1 is specific to the headwind flow simulation over the 10m cube, however it was used to derived nondimensional characterization relations. The nondimensional position of the arch vortex center line is given by

$$\begin{aligned}\bar{y} &= 1.55\bar{x}^2 + 1.2, \\ \bar{z} &= -1.5H,\end{aligned}\tag{4}$$

where the coordinates $\bar{x}$, $\bar{y}$, and $\bar{z}$ have been nondimensionalized by obstacle width W , height H and length L , respectively. From Eq. (4), the arch vortex center is assumed to be a 2D parabola that exists in the $\bar{z} = -1.5H$ plane, see Figure 11.

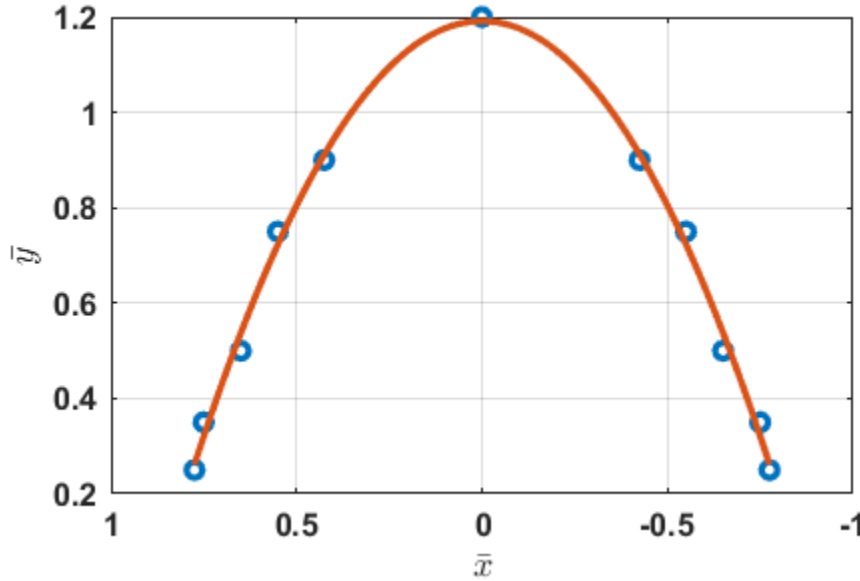


Figure 11: Parabolic representation of arch vortex in the $\bar{z} = -1.5H$ plane; blue points represent points from Table 1 and the red line represents the quadratic fit.

An expression for the nondimensional vortex core radius was similarly derived as a function of the nondimensional vertical coordinate $\bar{y}$:

$$\bar{r}_c = -0.90\bar{y} + 1.27.\tag{5}$$

From Table 1, the strength of the vortex in the different planes are close to each other, indicating viability of the vortex modeling approach. We averaged the corresponding values and nondimensionalized them using the freestream velocity magnitude of 30m/s and obstacle height $H = 10\text{m}$ to obtain a nondimensional arch vortex strength of

$$\bar{\Gamma} = \frac{\Gamma}{U_\infty H} = \frac{31.7 \text{ m}^2/\text{s}}{(30 \text{ m/s})(10 \text{ m})} = 0.106.\tag{6}$$

The applicability of the relations in Eqs. (4) through (6) for flow aft of obstacle of differing sizes is being explored in ongoing work. Here the arch vortex was represented as a parabolic vortex filament with a ground mirror counterpart and a numerical vortex model that combined the Biot-Savart law with the Vatisstas viscous core model [49] was implemented to obtain associated induced velocity predictions for further verification of the methodology. The ground mirror filament helped satisfy Helmholtz condition which states that vortex filaments must form a closed loop. The velocity induced by this arch vortex at a point located at position $\mathbf{r}$ relative to discretized vortex filament element $d\mathbf{l}$ was given by

$$\mathbf{V}_{ind} = \frac{\Gamma h}{4\pi(r_c^{2n} + h^{2n})^{1/n}} \int \frac{d\mathbf{l} \times \mathbf{r}}{|\mathbf{r}|^3} \times fac, \quad (7)$$

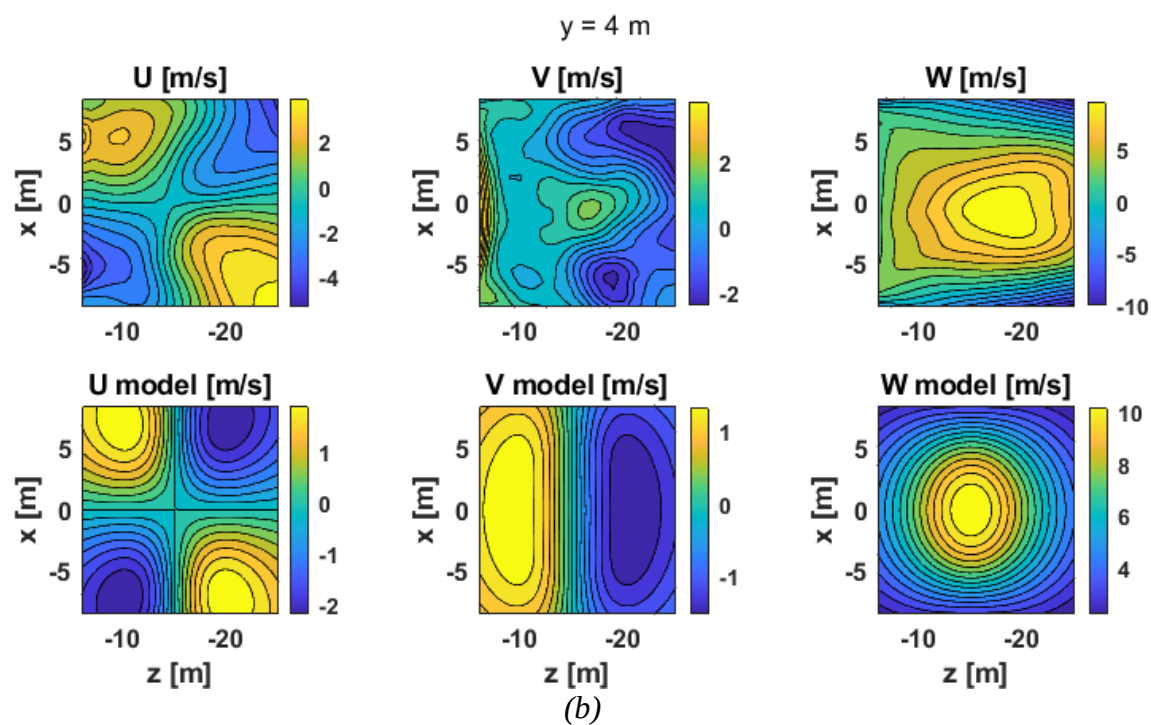
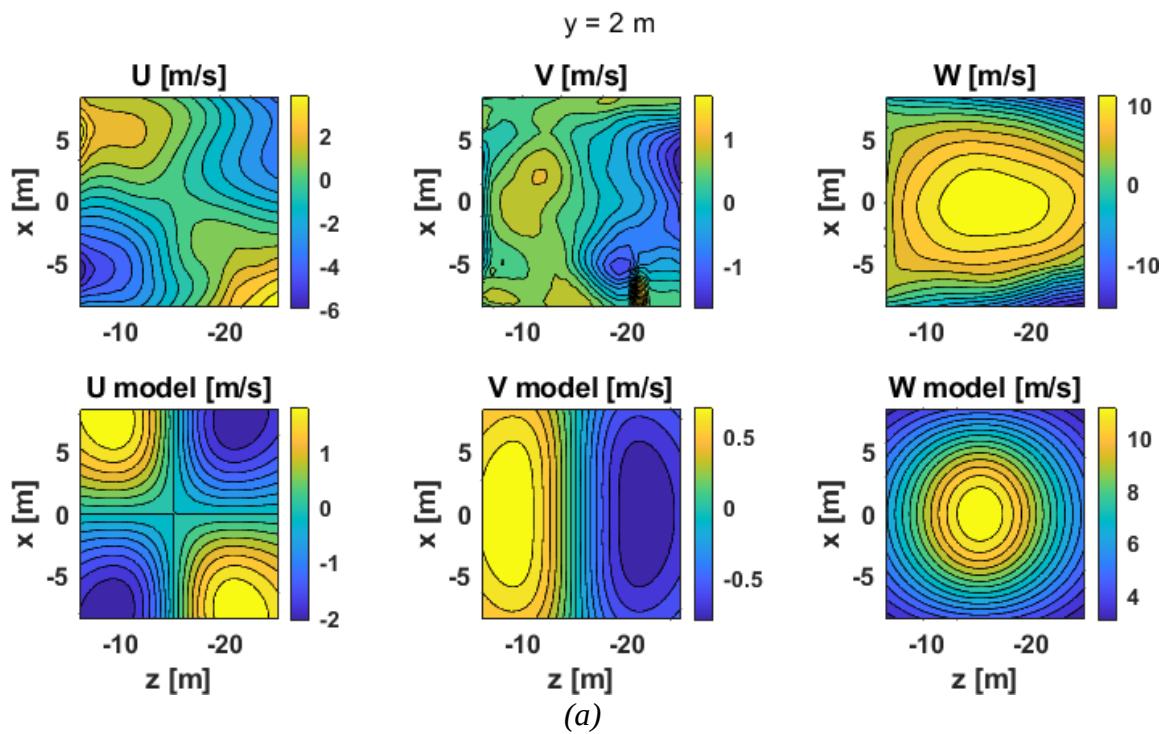
where h is the perpendicular distance of the evaluation point from the vortex filament element, n is an integer that controls the smoothness of the transition of the velocity predictions from the viscous core to the external inviscid region (we used $n = 1$), and fac is a scaling factor that varies with the nondimensional vertical coordinate $\bar{y}$ that we found necessary to include for accurate velocity magnitude predictions:

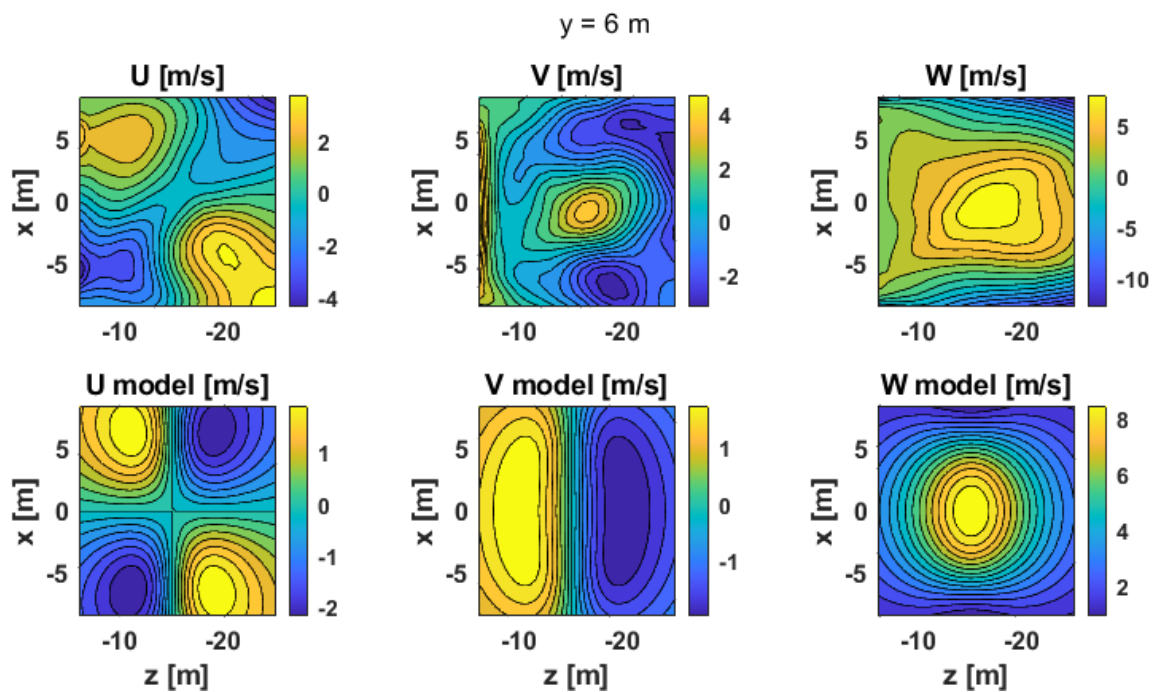
$$fac = -25\bar{y} + 25. \quad (8)$$

The induced velocities determined using Eq. (7), together with those from CGE/VorTran-M for the $y = \{2,4,6,8,10\}$ m and $x = \{1,3,5,7,9\}$ m planes for the 30m/s headwind flow over the 10m cube are plotted in Figure 12 and Figure 13, respectively. Note that the CGE/VorTran-M predictions include influence from all flow features whereas those of the vortex model only represent those from the arch vortex.

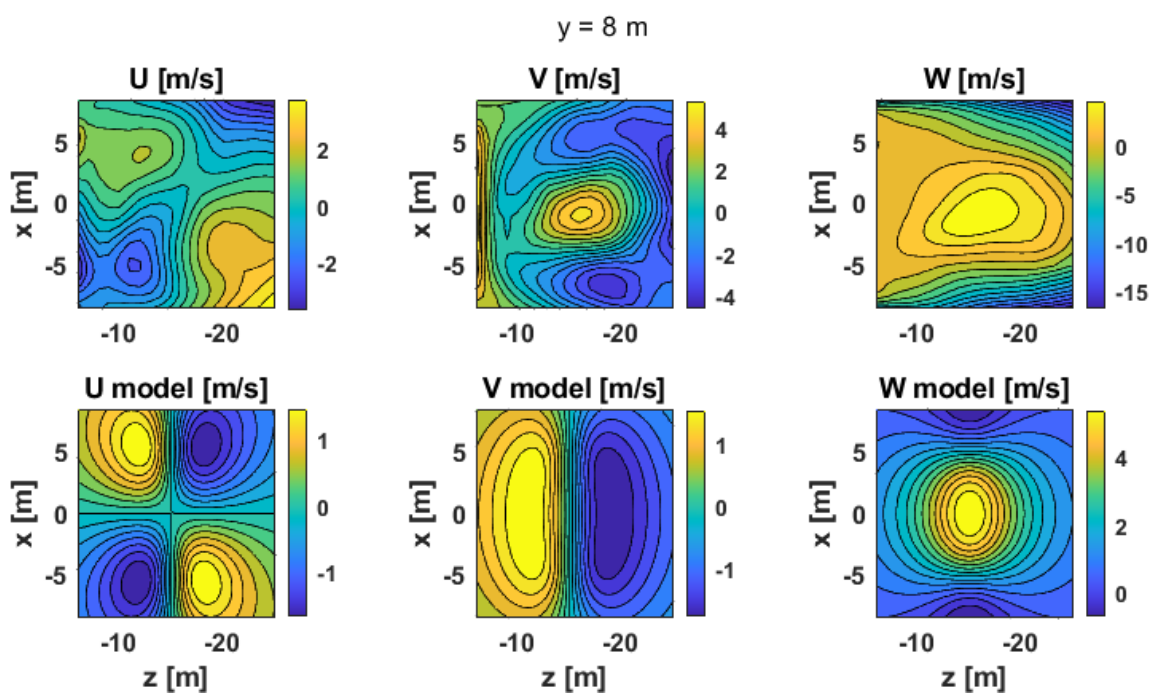
We make the following observations from the Figures:

- For the $y=\text{constant}$ planes, the lateral velocity U component predictions from the model exhibit similar magnitudes and spatial distributions as the CGE/VorTran-M predictions, while for the $x=\text{constant}$ planes, the model prediction for U are similar to those from CGE/VorTran-M only in the $x=5\text{m}$ and $x=7\text{m}$ planes, with some discrepancies noted downstream in the $z<-20\text{m}$ and $y>10\text{m}$ regions.
- For the $y=\text{constant}$ planes, the model predicts an antisymmetric vertical velocity V distribution about $z=-15\text{m}$, which bears some resemblance to the predictions from CGE/VorTran-M but does not fully capture the expected velocities and magnitude, a mismatch which could be potentially improved by accounting for additional flow feature models. This mismatch is noted in the $x=\text{constant}$ planes as well, although to a lesser extent, indicating the potential viability of the arch vortex model.
- For both the $y=\text{constant}$ and $x=\text{constant}$ planes, peak longitudinal velocities W are adequately captured by the model in all planes except the $y=10\text{m}$ plane. Additionally, the peak longitudinal velocity regions predicted by the model covers a smaller spatial domain than those from CGE/VorTran-M.
- Predictions from the arch vortex model show reasonable agreement with expected velocities in the domain bounded approximately by $x \in [-5,5]\text{m}$, $y \in [2,9]\text{m}$ and $z \in [-25,-10]\text{m}$, which corresponds to $x \in [-W/2, W/2]$, $y \in [0.2, 0.9]H$ and $z \in [0.5, 2]H$ aft of the obstacle.





(c)



(d)

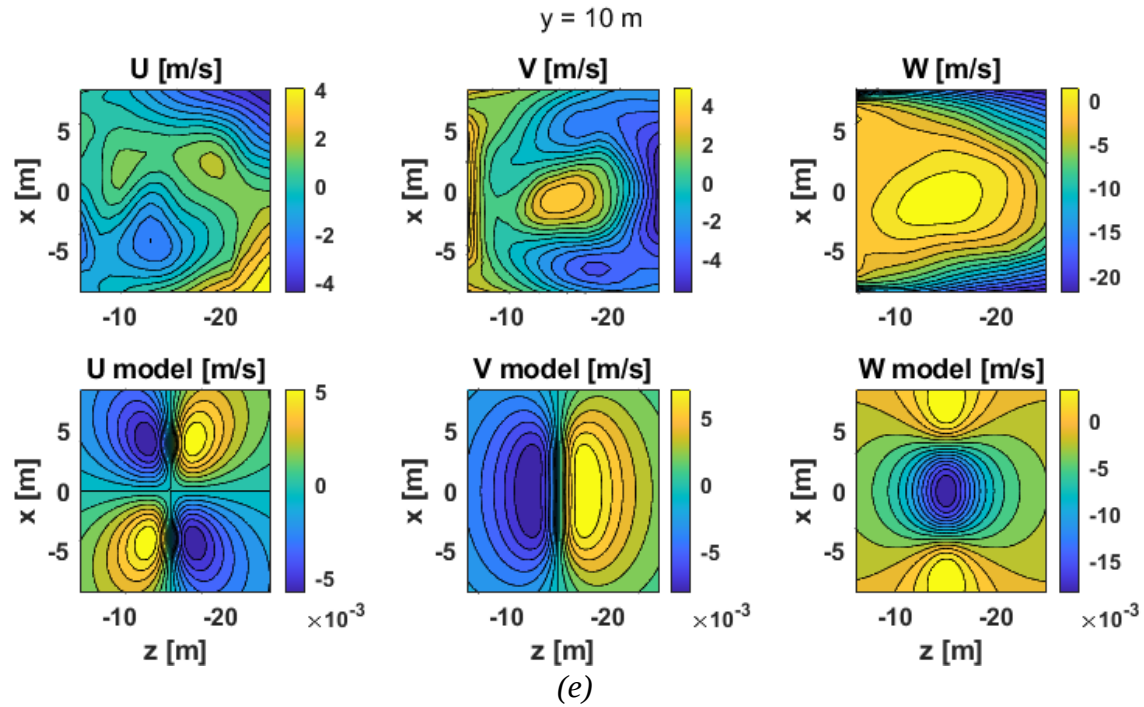
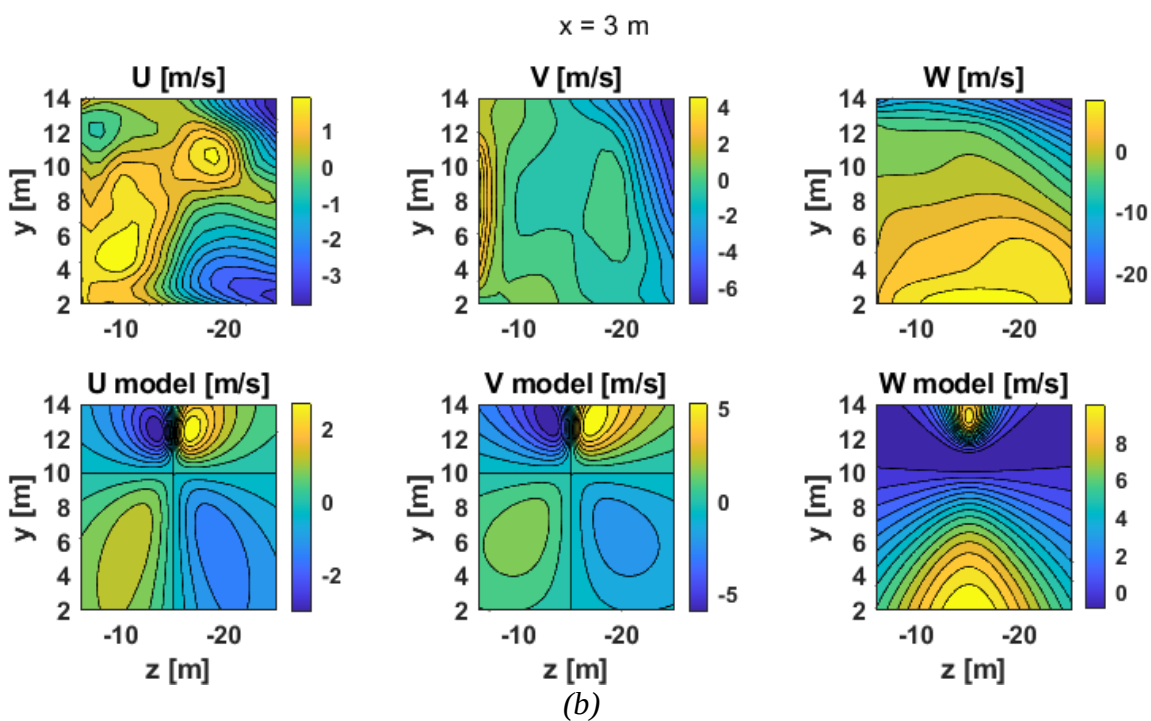
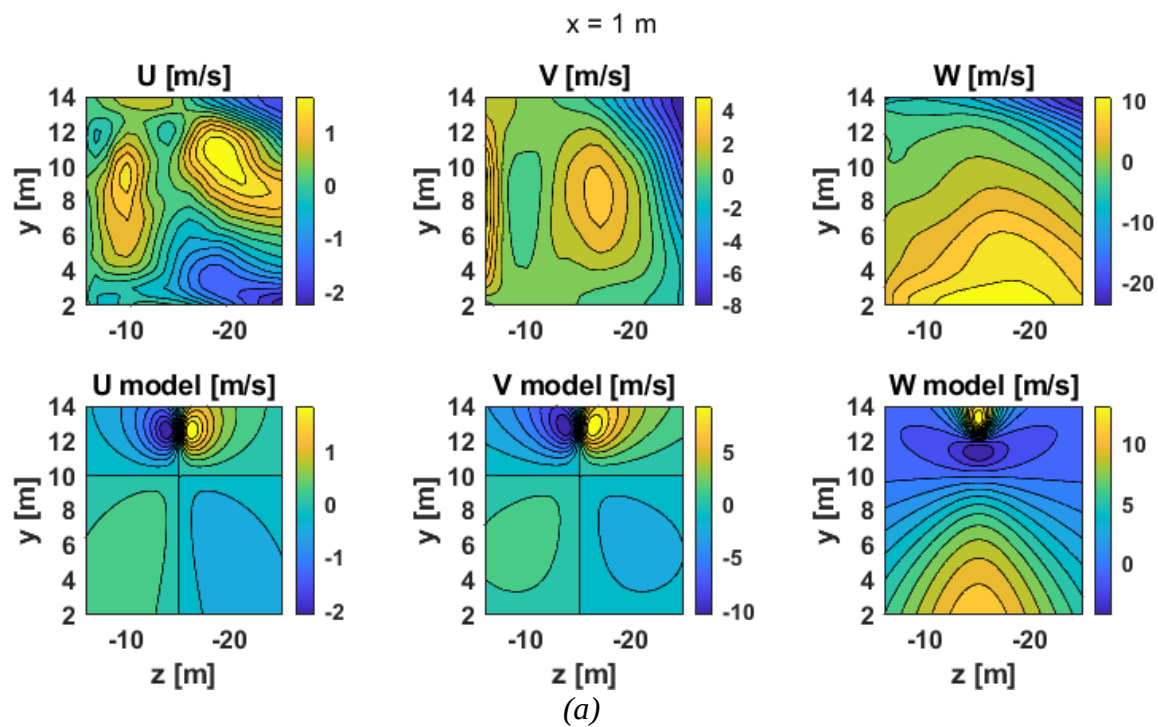
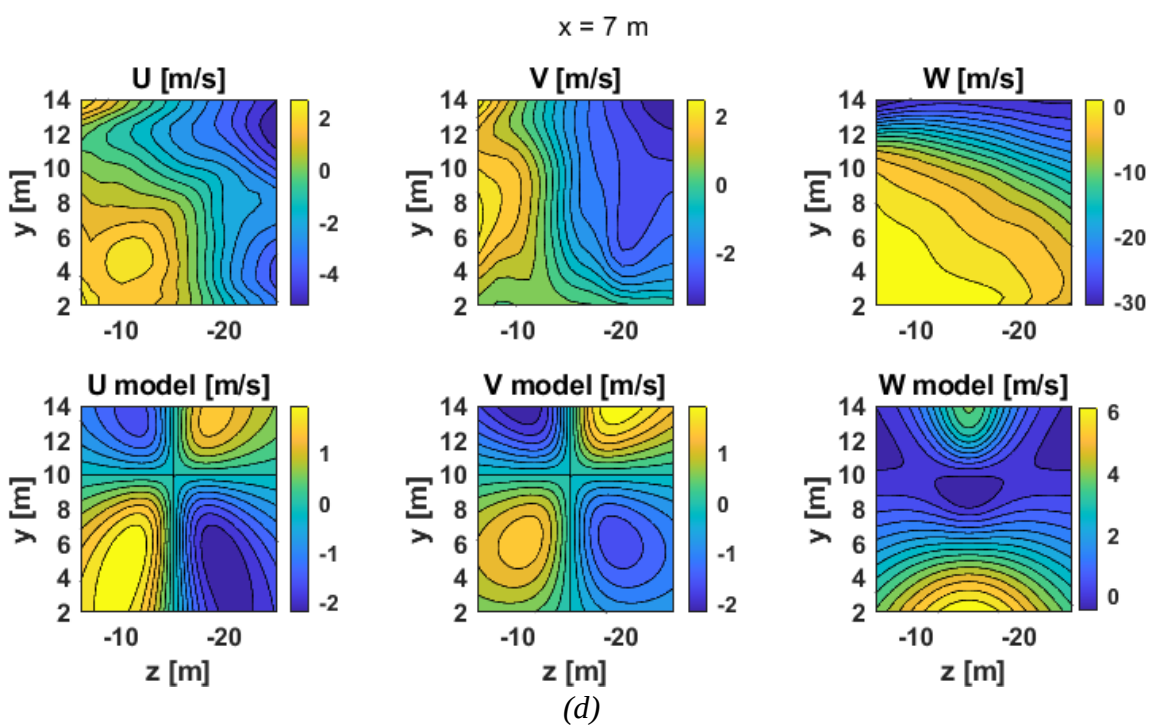
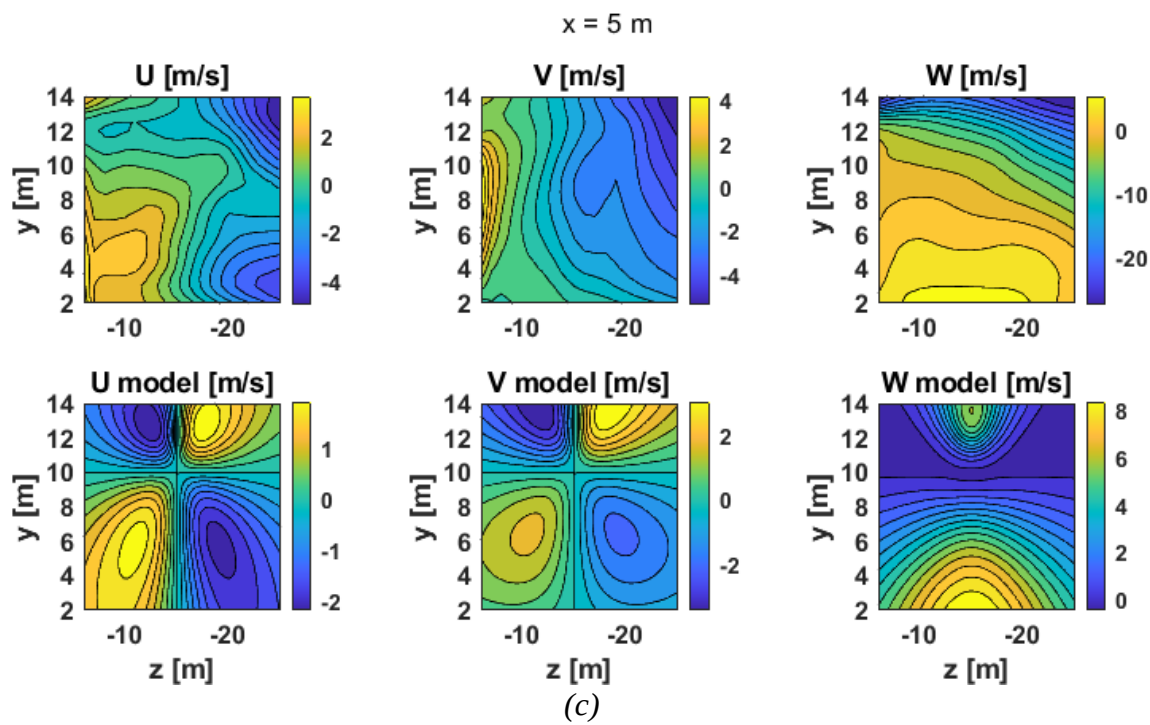


Figure 12: Contours of airwake velocity components aft of the 10m obstacle for various $y=\text{constant}$ planes obtained using CGE/VorTran-M and arch vortex model.





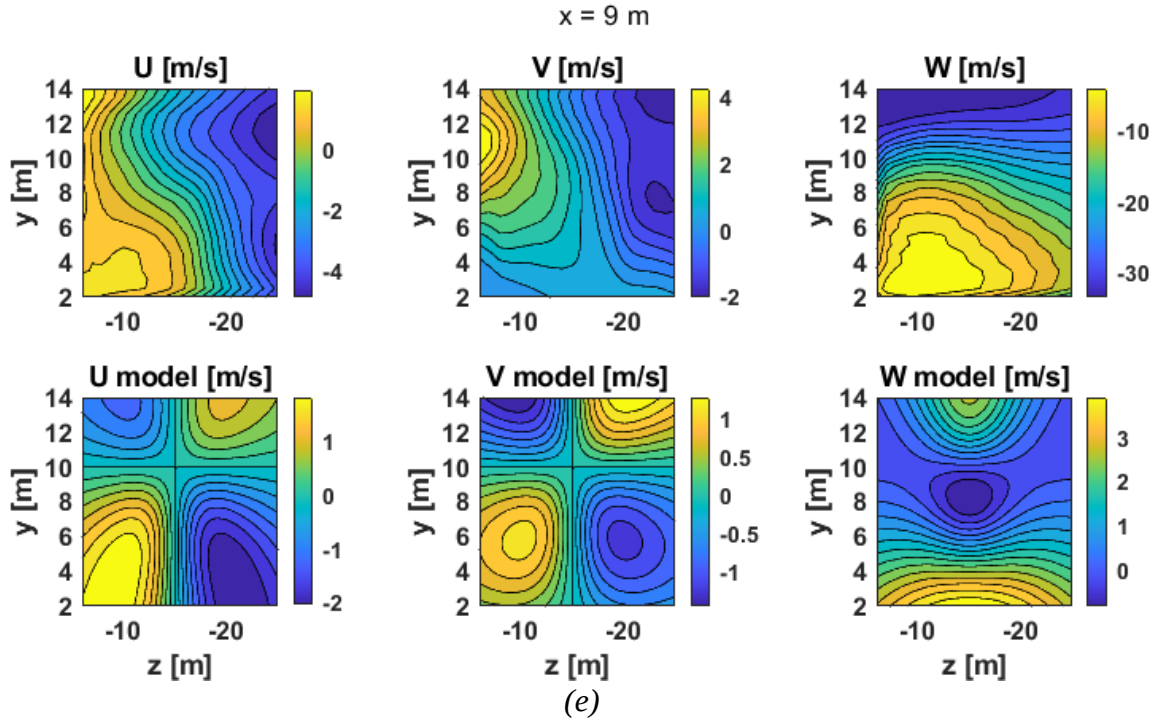


Figure 13: Contours of airwake velocity components aft of the 10m obstacle for various $x=\text{constant}$ planes obtained using CGE/VorTran-M and arch vortex model.

Scalable Analytical Models for Time-Averaged Longitudinal and Vertical Velocity Components

The analytical model methodology employs piece-wise functions to reconstruct the time-averaged velocity profile across different regions. Longitudinal velocity model is considered first, and is derived from a vortex model introduced by Banks and Meroney [50] and can be thought of as a wheel being spun at two points: point M_{upper} at a velocity $U_{M_{upper}}$ and point M_{lower} at a velocity $U_{M_{lower}}$, see Figure 14.

Input parameters to model consist of:

1. location of vortex center (r_c).
2. vortex radius (h),
3. vortex core radius fraction (c)
4. location of point M_{upper} ($R_{M_{upper}}$),
5. location of point M_{lower} ($R_{M_{lower}}$),
6. velocity at point $R_{M_{upper}}$ ($U_{M_{upper}}$),
7. velocity at point $R_{M_{lower}}$ ($U_{M_{lower}}$),
8. location of point close to ground (r_0) below which the constant velocity was assumed, and
9. velocity near ground (U_0).

Sample longitudinal velocity predictions obtained using the model are given in Figure 15 for $z=-18\text{m}$ along the mid plane shown in Figure 7(a).

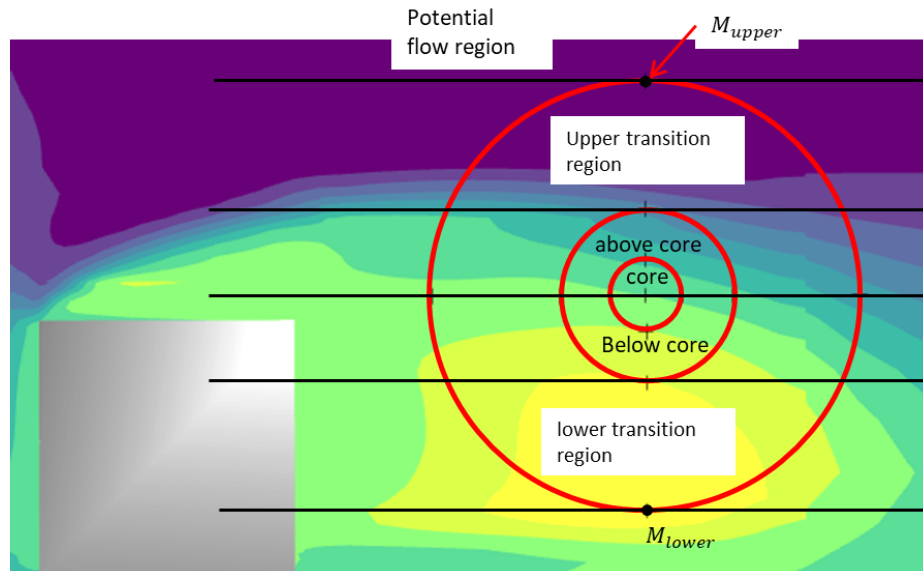


Figure 14: Illustration of modified Banks and Meroney vortex model shifted upwards.

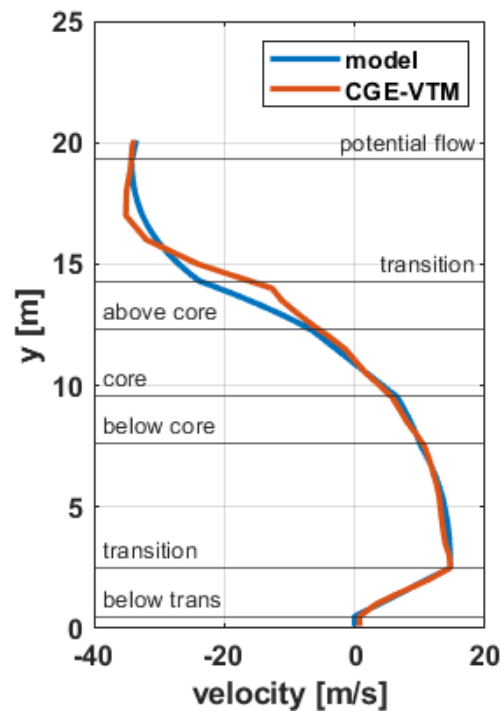


Figure 15: Longitudinal velocity profile along a vertical line through $z=-18\text{m}$ in the lee of the cube obtained using the analytical model.

We derived nondimensional expressions for the model inputs by fitting polynomial functions on their spanwise variation along the $x=0\text{m}$ midplane shown in Figure 7(a). Distance parameters $r_c, h, R_{M_{upper}}, R_{M_{lower}}$ and r_0 were nondimensionalized using the obstacle height H while the

velocity parameters $U_{M_{upper}}$, $U_{M_{lower}}$ and U_0 were nondimensionalized using freestream speed U_∞ . The resulting expressions are:

$$\begin{aligned}
 \bar{r}_c(\bar{z}) &= -0.07\bar{z}^2 + 0.081\bar{z} + 0.93, \\
 \bar{h}(\bar{z}) &= 0.024\bar{z} + 0.28, \\
 \bar{c}(\bar{z}) &= -0.17\bar{z} + 0.57, \\
 \bar{R}_{M_{upper}}(\bar{z}) &= 1.56, \\
 \bar{R}_{M_{lower}}(\bar{z}) &= 0.094\bar{z} + 0.14, \\
 \bar{U}_{M_{upper}}(\bar{z}) &= 0.06\bar{z}^2 - 0.088\bar{z} - 1.15, \\
 \bar{U}_{M_{lower}}(\bar{z}) &= -0.36\bar{z}^2 + 0.92\bar{z} - 0.13, \\
 \bar{r}_0(\bar{z}) &= -0.0017\bar{z} + 0.015, \\
 \bar{U}_0 &= -0.25.
 \end{aligned} \tag{9}$$

By scaling expressions for distance parameters by obstacle width, and velocity expressions by freestream magnitude, we demonstrated that these relations could be employed to obtain longitudinal velocity predictions in the $y=5m$ plane shown in Figure 7(b) as well. Similarly, if we dimensionalized the distance expressions by $L_c = 1.2L$, we could also recover representative velocity profiles along the diagonal plane shown in Figure 7(c).

A similar approach was followed in deriving relations for the vertical velocity, which is particularly important for rotorcraft applications given that this velocity component directly influences rotor inflow, which, in turn, affects rotor loads and consequently aircraft flight dynamics, handling qualities and ride qualities. A custom piece-wise analytical model was devised consisting of first and second order polynomials to fit the velocity component profile. This is depicted in Figure 16, which shows a typical vertical velocity profile and the four regions where polynomial fitting is performed. A linear fit is employed in regions #1 and #3 and a second order fit in regions #2 and #4. Model input parameters consist of:

1. velocity near ground (v_0);
2. location where region #1 ends and region #2 starts (r_1);
3. velocity at r_1 (v_1);
4. location where region #2 ends and region #3 starts (r_2);
5. velocity at r_2 (v_2);
6. velocity in the middle of region #2 (v_{2m});
7. location where region #3 ends and region #4 starts (r_3);
8. velocity at r_3 (v_3);
9. location where region #4 ends (r_4);
10. velocity at r_4 (v_4); and
11. velocity in the middle of region #4 (v_{4m}).

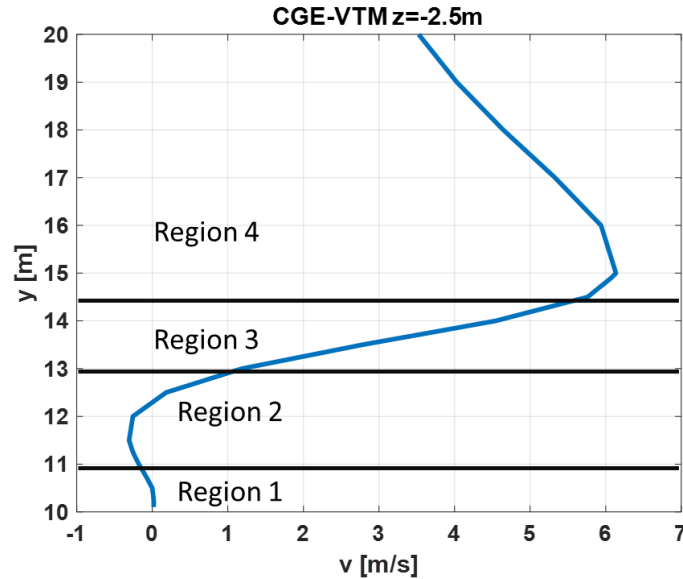


Figure 16: Typical vertical velocity profile from CGE/VorTran-M highlighting the four regions considered in the fitting model.

Sample model fitting results for the vertical velocity profile over the top surface along the midplane shown in Figure 7(a) are shown in Figure 17. Note that velocities near the ground are not necessarily zero because the predictions shown were inviscid and CGE/VorTran-M enforces the no-penetration boundary condition at walls by setting the convective flux, not velocity, through the cell face corresponding to the wall to zero. The model shows good agreement with CGE/ VorTran-M results in the figure. Regions #3 and #4 are the primary ones present closer to the leading edge at $z=5\text{m}$ and $z=2.5\text{m}$. Further downstream, region #2 emerges indicating the presence of recirculation. This is evident from the slight negative vertical velocities noted at $z=-2.5\text{m}$ in the $y \in (0,2]\text{m}$ range and further confirmed from the Tecplot contour plot of time-averaged vertical velocity and shown in Figure 18.

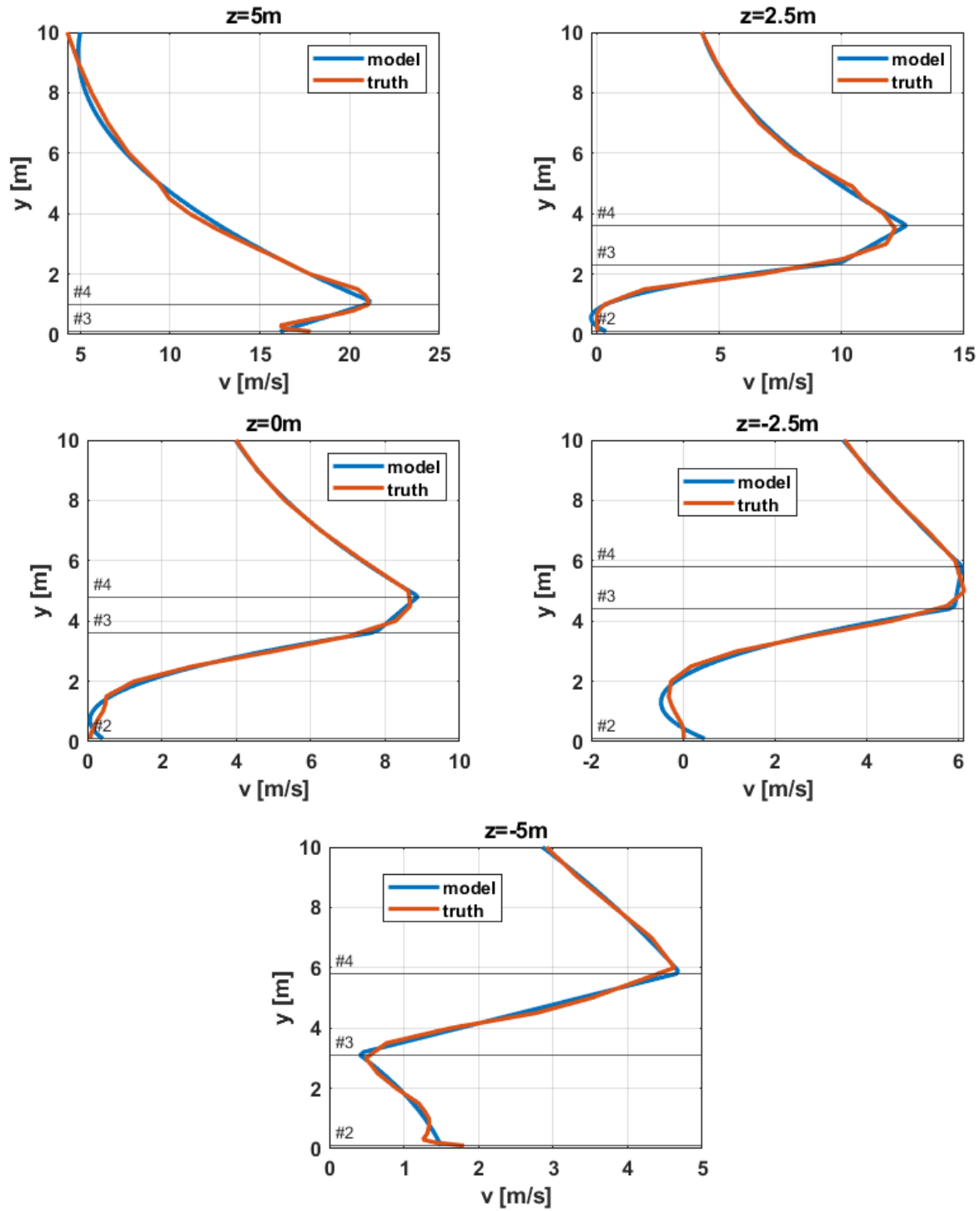


Figure 17: Time-averaged vertical velocity over top surface along $x=0\text{m}$ plane.

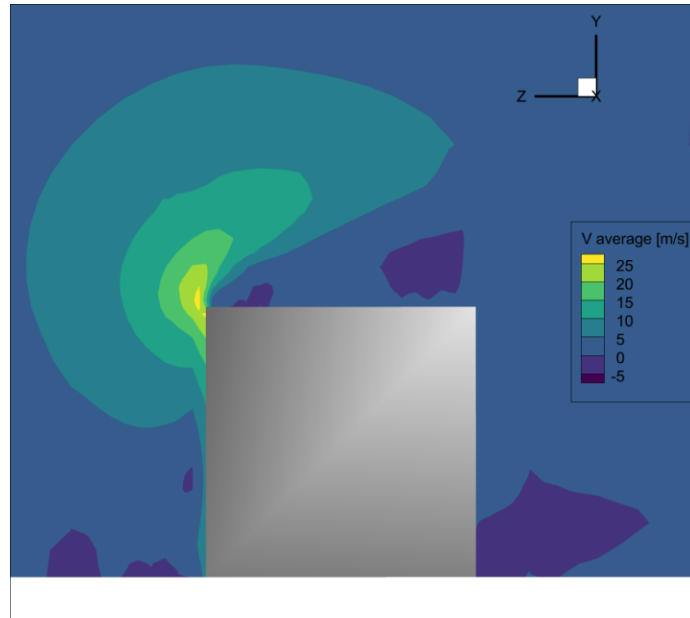


Figure 18: Time-averaged vertical velocity contour along $x=0m$ plane.

Three-dimensional velocity reconstruction was performed by generating a database of position coordinates and corresponding velocities along the three planes shown in Figure 7 and using MATLAB's `scatteredInterpolant`⁷ capability to “blend” the velocities. Provided with a 2D or 3D scattered dataset, this MATLAB function returns a function handle that outputs interpolated values for user specified position coordinates. This capability supports several interpolation and extrapolation methods, and `linear` interpolation and `nearest` extrapolation were employed in this work. Velocity predictions using the simplified relations along the transverse plane shown in Figure 19 are compared to CGE/VorTran-M predictions in Figure 20 for headwind flow over the 10m cube. The recirculation region represented by the model appears to be smaller than that predicted by CGE/VorTran-M, but the results are quite promising given the simplistic relations being employed. The discontinuities or kinks noted in the analytical contours represent the planes along which the 2D model fitting was performed. Similar reconstructions were achieved for regions over the obstacle as seen in Figure 21, where predictions along a similar transverse plane across the cube are plotted. These results further confirm the viability of the analytical models.

⁷ <https://www.mathworks.com/help/matlab/ref/scatteredinterpolant.html>

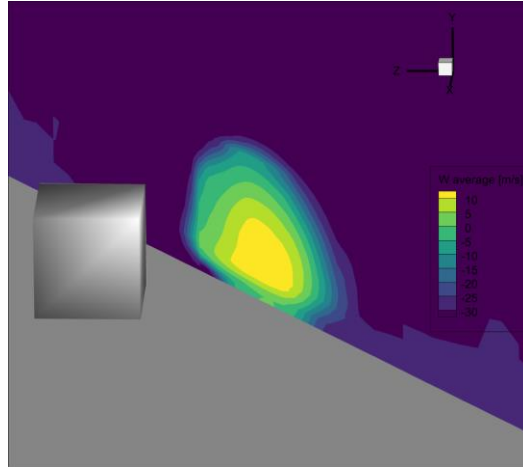


Figure 19: Transverse plane considered in parametric model evaluation.

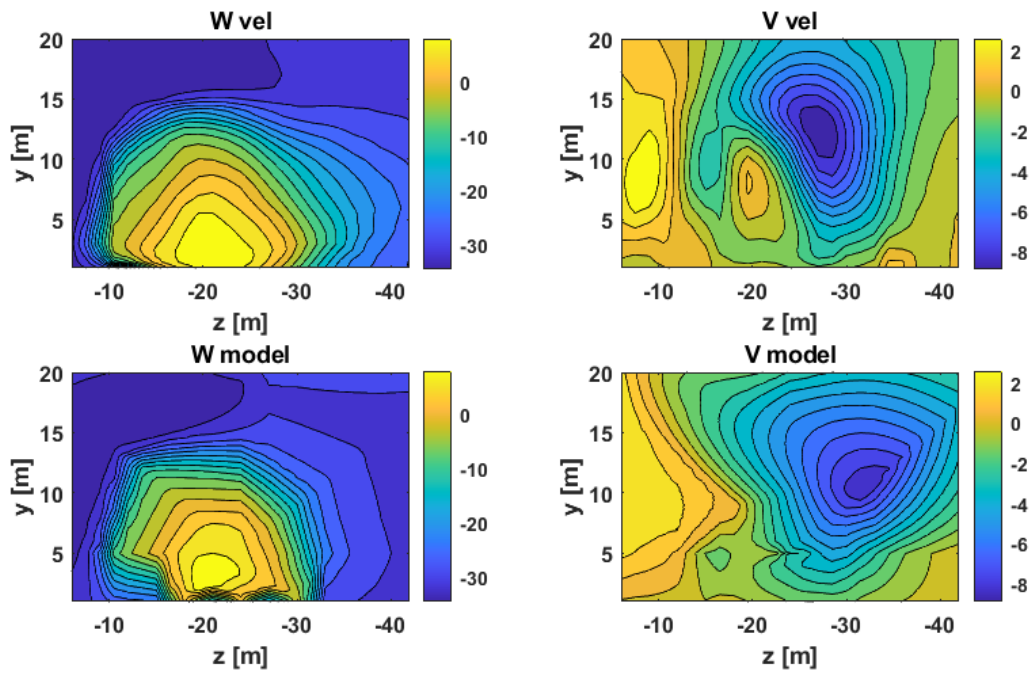


Figure 20: Mean longitudinal velocity (left) and vertical velocity (right) contours along transverse plane; CGE/VorTran-M (top) and analytical model (bottom).

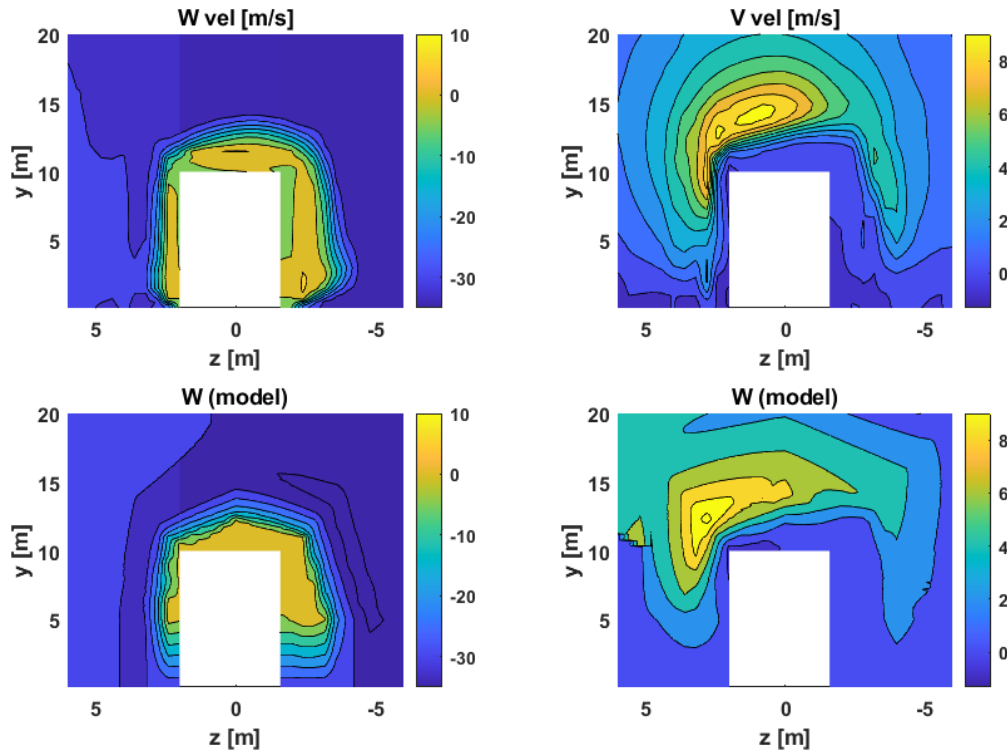


Figure 21: Mean longitudinal velocity (left) and vertical velocity (right) contours along transverse plane through the cube; CGE/VorTran-M (top) and parametric model (bottom).

The geometric scalability of the relations given in Eq. (9) was evaluated by considering a 30 m/s headwind flow over a rectangular obstacle that is 30 m wide, 10 m long and 10 m high. For this wider configuration, the recirculation region extends further downstream when compared to the cube but still exhibits similar longitudinal velocity profiles. Constant x , y and z stretch factors were introduced that when employed with the relations given in Eq. (9), allowed adequate velocity profiles to be obtained. For instance, if a constant z -coordinate stretch factor of 0.5 is employed, the velocity profiles predicted by Eq. (9) cover twice the longitudinal distance aft of the obstacle. By default, all stretch factors are 1. The stretch factors for the cuboid were determined manually by comparison with CGE/VorTran-M data, and one of the immediate tasks in following work is to derive relations for these scaling factors by considering additional rectangular configurations.

Model predictions for a transverse plane similar to that shown in Figure 19 are shown in Figure 22 for the wider configuration. Despite the smaller size of the peak recirculation region predicted by the model, good agreement is noted with CGE/VorTran-M results. The larger size of the recirculation region is apparent in the contour plots. Work is currently underway to test the scaling of the vertical velocity relations.

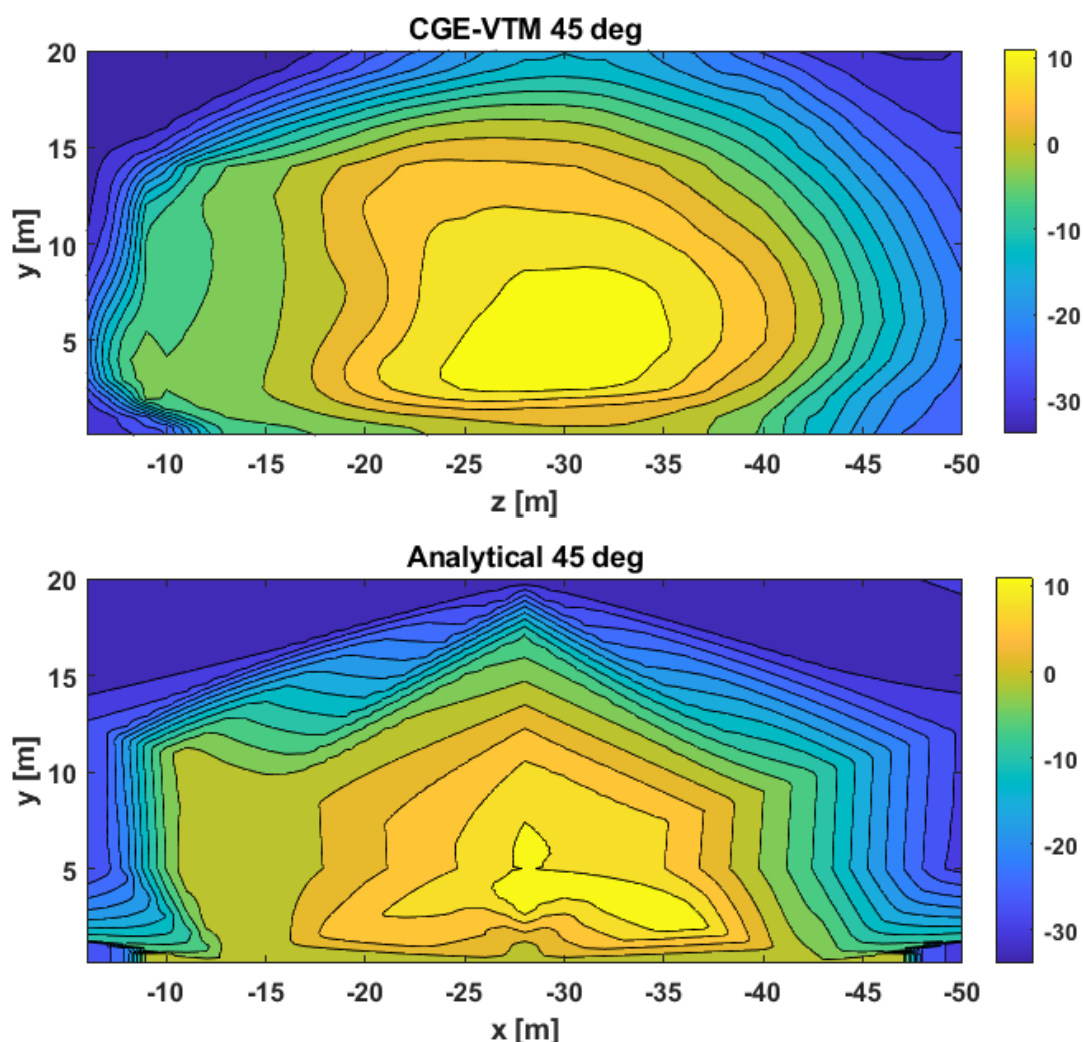


Figure 22: Mean longitudinal velocity contours along transverse plane aft of 30m wide cuboid; truth (top) and parametric model (bottom).

Dynamic Characterization

A spatiotemporal characterization of the flow features shown in Figure 7 is critical for a better understanding of the ship-helicopter dynamic interface. Although this fact is generally accepted, work in literature has typically focused on the identification of coherent structures with limited characterization of the time dynamics associated with them. Spatiotemporal characterization of fluid dynamics is typically performed using modal decomposition methods that attempt to represent unsteady flows with random fluctuations as superpositions of deterministic basis vectors or “modes” that can provide better insights into flow behavior [51]. Two popular methods are the proper orthogonal decomposition (POD) [51-54] and dynamic modal decomposition method (DMD) [55-58].

POD follows the classical separation of variables approach to solving partial differential equations (PDEs) and represents quantities of interest (e.g., velocity) as a superposition of spatial basis vectors and corresponding temporal coefficients. Emphasis is typically placed on determining the orthonormal spatial basis functions that are computed using the spatial covariance matrix of quantities of interest (e.g., velocity, pressure) [51]. The temporal

coefficients are determined from the spatial basis vectors and provided quantity data. The covariance matrix indicates how a change in a quantity of interest at any given spatial location is associated with changes in the rest of the domain. That is, it gives a measure of data correlation, which, also gives a measure of turbulent kinetic energy (TKE) when the quantity of interest is velocity [51]. The TKE is a metric used to quantify flow turbulence and is defined as [59]

$$TKE = \frac{1}{2} (\overline{u'^2} + \overline{v'^2} + \overline{w'^2}), \quad (10)$$

where, $\overline{u'}$, $\overline{v'}$, $\overline{w'}$ represent average fluctuating longitudinal, lateral, and vertical velocity components,

$$\overline{u'} = \frac{1}{T} \int_0^T (u(t) - \bar{u}) dt, \quad (11)$$

and where $u(t)$ is the instantaneous velocity and $\bar{u}$ is the average velocity at the location. The $\overline{v'}$, and $\overline{w'}$ terms have similar definitions. The spatial modes obtained using POD are orthonormal and each have different TKE levels associated with them. The most energetic ones can be further examined to identify the primary coherent structures responsible. POD is considered an energy decomposition method [53]; however each mode can be associated with a wide range of time scales (frequencies), which makes a proper spatiotemporal characterization of flow features nontrivial.

The DMD method on the other hand, is a frequency decomposition method where each resulting mode is associated with one unique frequency, thus providing information on both the length and time scales of coherent structures [53, 55, 57]. In this method, nonlinear systems are mapped onto a linear space (generally with infinite-dimension) using a linear operator. The formulation is such that eigenvalue decomposition of the linear operator allows for the identification of coherent structures in the flow using the DMD modes, and their growth/decay rates and frequencies using the eigenvalues. Note that the DMD modes are different from the eigenvectors obtained from eigenvalue decomposition [55, 57] in that the DMD modes are not ranked by energy levels and are not orthonormal. Since both spatial *and* temporal aspects are considered in the DMD characterization, various criteria have been proposed to identify the dominant DMD modes, each with varying performance for given flow configurations [55]. This method is generally preferred for flow reconstruction of periodic system since it places emphasis on spectral purity of the decomposition (distinct frequencies for each mode). For unsteady, nonlinear systems, frequency modulations, phase jitter and other localized frequency events are not readily captured. Moreover, the large number of modes required to capture major flow dynamics in the time domain often leads to redundancy in the structure of the spatial domain [53].

Given the limitations of POD and DMD, several hybrid methods have been developed to characterize flow dynamics in terms of energy content and spectral purity. In this work, we employ a multi-resolution POD method based recent work by Zhu et al. [54], where frequency ranges or “bins” that contain the most energetic features are first identified, before performing POD to identify the associated coherent structures. Resolving the energetic features into frequency bins allows for a more intricate spatiotemporal characterization of flow dynamics, when compared to a POD, as the frequency ranges are typically narrow and more specific to coherent structures.

Multi-Resolution Proper Orthogonal Decomposition

Several coherent structures spanning a range of length and time scales exist in typical ship airwake. For the ship-helicopter DI, the most energetic coherent features are of interest since these influence aircraft flight dynamics and handling qualities. The multi-resolution POD method isolates these coherent features by identifying and analyzing airwake data only within frequency ranges where these energetic features exist [54]. There are three primary steps involved:

- identify the most energetic features and the N_{bin} frequency bins in which they exist,
- filter the original data using bandpass filters to generate N_{bin} datasets corresponding to the ranges of each frequency bin, and
- perform POD of the individual filtered datasets to identify the primary coherent features within each frequency range.

This approach allows for a more intricate characterization of the spatial *and* temporal scales of the most energetic features of the airwake.

The method begins with arranging CFD (or experimental) velocity data into a 2D matrix as follows [54]

$$D(x, t) = \begin{bmatrix} d(x_1, t_1) & d(x_1, t_2) & \cdots & d(x_1, t_{N_t}) \\ d(x_2, t_1) & d(x_2, t_2) & \cdots & d(x_2, t_{N_t}) \\ \vdots & \vdots & \ddots & \vdots \\ d(x_{N_v \cdot N_s}, t_1) & d(x_{N_v \cdot N_s}, t_2) & \cdots & d(x_{N_v \cdot N_s}, t_{N_t}) \end{bmatrix}, \quad (12)$$

where each quantity d represents a mean-subtracted flow velocity at a given spatial location x and instant in time t . There are N_t time steps (uniform discretization assumed), N_v velocity components and N_s spatial locations. In this work, longitudinal and vertical velocities will be considered individually such that only one velocity component is included in the data matrix D . The order of the spatial discretization as vectors in the data matrix is not exclusive. The procedure of obtaining the vectoral discretization from the physical space should be reversed when interpreting results from the POD [54]. The next step is to take the fast Fourier transform (FFT) in time for each row of the data matrix

$$\hat{D}(x, \omega) = \text{FFT}\{D(x, t)\} \quad (13)$$

and subsequently compute the cross-spectral density matrix

$$\hat{K} = \frac{1}{N_t} \hat{D}^* \hat{D}, \quad (14)$$

where “*” indicates conjugate transpose. Each element on diagonal of matrix $\hat{K}$ represents the TKE at given frequency [54]. Half of the values correspond to positive frequency values and the other half to negative frequencies, evident from symmetry in the diagonal values. The TKE values can be plotted to determine the N_{bin} frequency ranges or bins where highly energetic flow features are present. These are readily identified from the peaks in the plot.

The next step is to filter⁸ the initial data matrix D from Eq. (12) row by row to generate N_{bin} data matrices, which are then analyzed using POD. The POD formulation diagonalizes the data matrix as follows

$$D = \Phi \Sigma \Psi^*, \quad (15)$$

where the columns of Φ contain the orthonormal spatial basis functions, Ψ describes the temporal evolution of the data, and Σ is a diagonal matrix with each entry σ providing a measure of the relative TKE of each spatial mode [54]. The most energetic modes can be identified by plotting the relative TKE contribution α_i of each mode

$$\alpha_i = \frac{\sigma_i}{\sum \sigma_i}. \quad (16)$$

The corresponding spatial modes can then be plotted to identify the primary coherent structures contributing to the TKE. For a more detailed and practical explanation of the POD method, the reader is directed to Ref. [51].

The multi-resolution POD approach was employed for the dynamic characterization of flow features using longitudinal and vertical velocity data aft of the obstacle along the midplanes shown in Figure 7(a) and Figure 7(b). Results for each are presented below.

Characterization Along $x=0m$ Plane: Longitudinal Velocity

The midplane shown in Figure 7(a) is considered first, and results are presented for longitudinal velocity. The approach laid out in the previous section was used to determine the cross spectral-density and the TKE associated with each frequency in data. The resulting normalized TKE values are plotted in Figure 23 as a function of Strouhal number. The freestream speed of 30 m/s and cube height of 10m were used as characteristic velocity and length, respectively. The largest peak is noted for the $St \in (0,0.02]$ bin. Although these St values appear smaller than expected, similarly values are reported by Zhu et al. in Ref. [54], though further investigation remains warranted to ascertain their validity. A bandpass filter was applied to the original data matrix to isolate flow features within this identified frequency range. The normalized TKE plot obtained from the cross-spectral density matrix of the filtered data is shown in Figure 24, where it is evident that the band-pass filter isolates the frequency bin of interest.

A POD of the filtered data is then performed. The TKE contribution of each mode α_i is plotted in Figure 25. Modes #1 and #2 contribute 58% and 26%, respectively, to the total TKE in that bin. Contour plots of these modes are shown in Figure 26 and Figure 27. From Figure 26, the primary coherent structure in mode #1 is the shear layer that is shed from the top edge of the cube and the associated back step recirculation aft of the cube. Note that flow does not reattach on the top surface of the cube in the simulation considered. The shear layer and aft recirculation contribute to 58% of the TKE associated with flow for $St \in (0,0.02]$. For mode #2, three distinct flow features are noted immediately aft of obstacle in Figure 27: the shear layer between $y=10m$ and $y=15m$, a recirculation region immediately below it and a secondary recirculation of opposite sign closer to the ground. The second and third features are likely due to the arch vortex aft of the cube and the ground horseshoe vortex, respectively (see Figure 6). The three features contribute to 26% of the TKE associated with flow for $St \in (0,0.02]$.

⁸ In this work, we employ a bandpass filter derived from the one presented in <https://tomroelandts.com/articles/how-to-create-simple-band-pass-and-band-reject-filters>

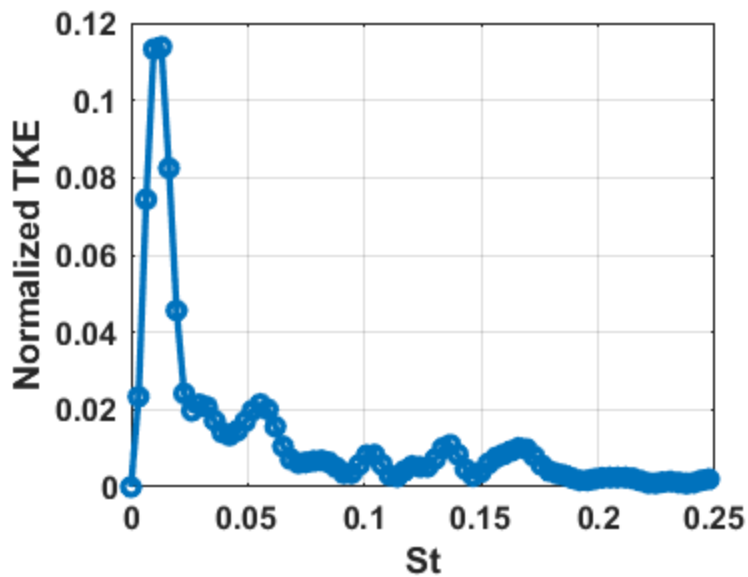


Figure 23: Normalized TKE for longitudinal velocity aft of the obstacle along $x=0m$ plane.

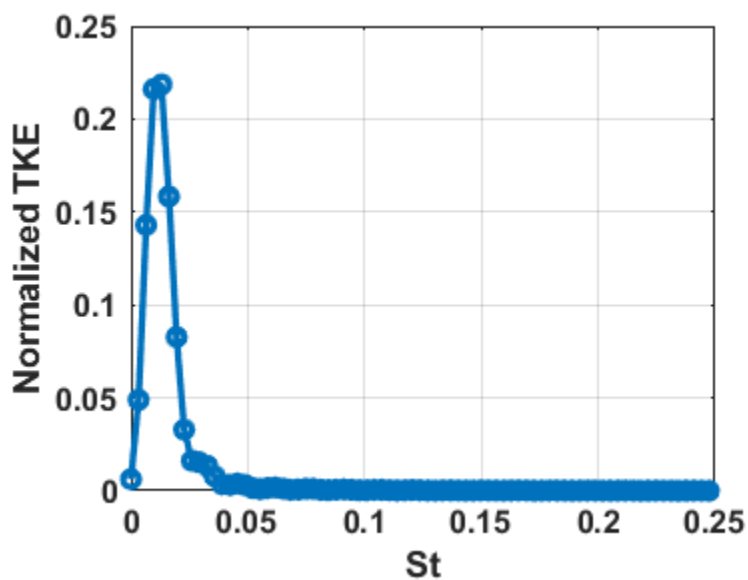


Figure 24: Normalized TKE for filtered longitudinal velocity data aft of the obstacle along $x=0m$ plane.

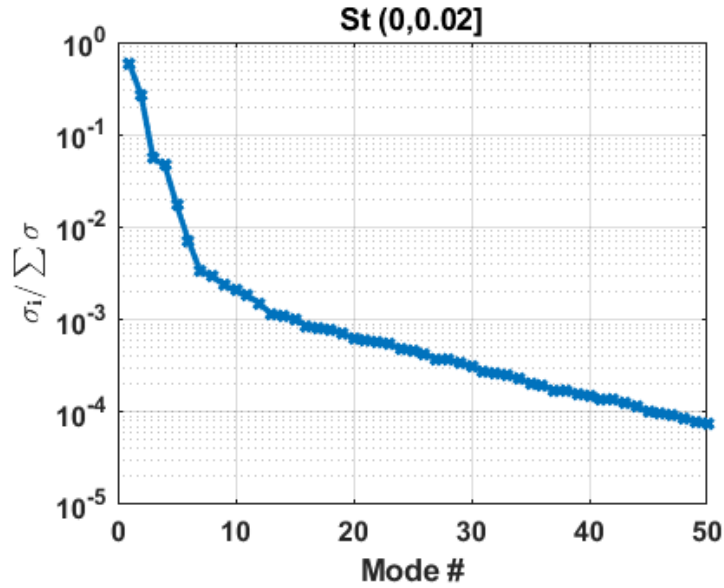


Figure 25: Contribution of each mode to total TKE in $St \in (0,0.02]$ bin; longitudinal velocity aft of the obstacle along $x=0m$ plane considered.

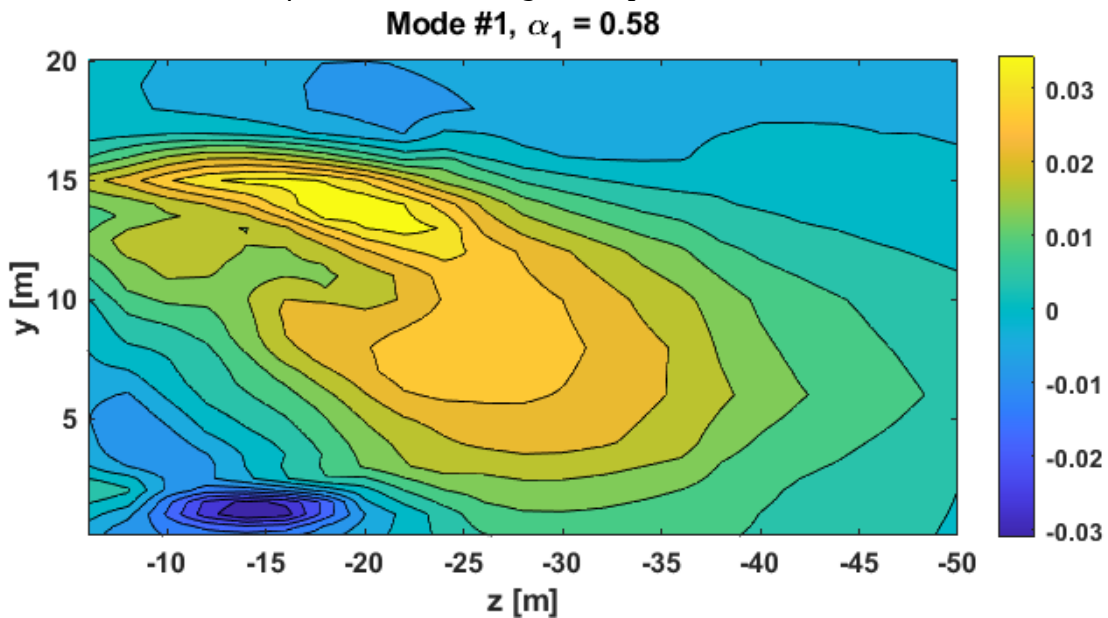


Figure 26: Mode #1 from POD analysis of longitudinal velocity data aft of the obstacle along $x=0m$ plane in $St \in (0,0.02]$ bin.

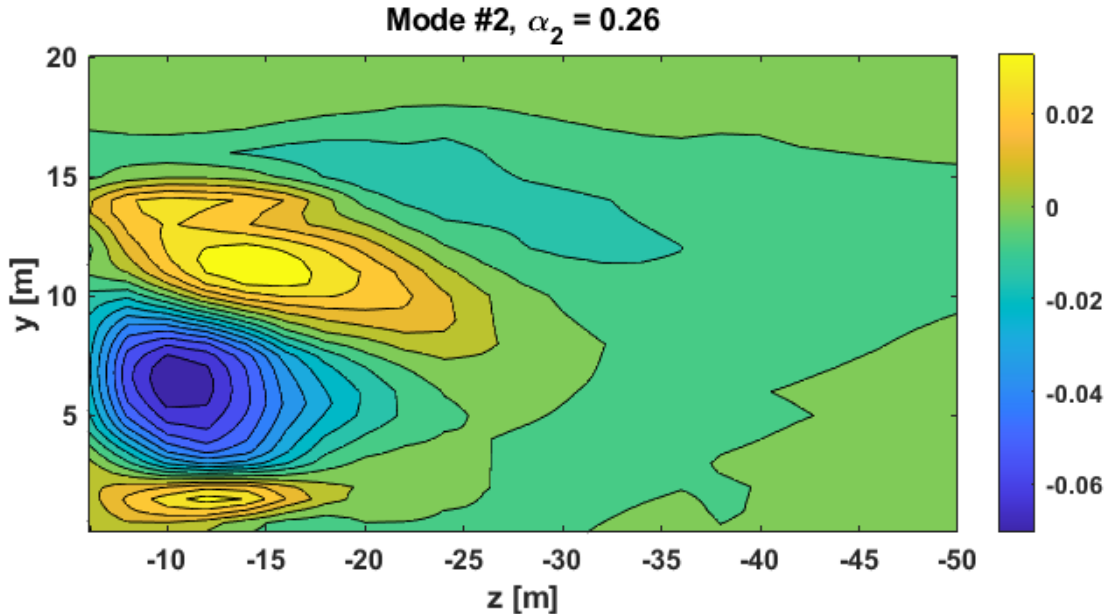


Figure 27: Mode #2 from POD analysis of longitudinal velocity data aft of the obstacle along $x=0\text{m}$ plane in $St \in (0,0.02]$ bin.

Characterization Along $x=0\text{m}$ Plane: Vertical Velocity

The vertical velocity component is particularly important for rotorcraft shipboard operations. The normalized TKE values obtained from the cross-spectral density matrix are plotted in Figure 28. Two frequency bins are identified from the figure: $St \in (0,0.03]$ and $St \in (0.03,0.065]$.

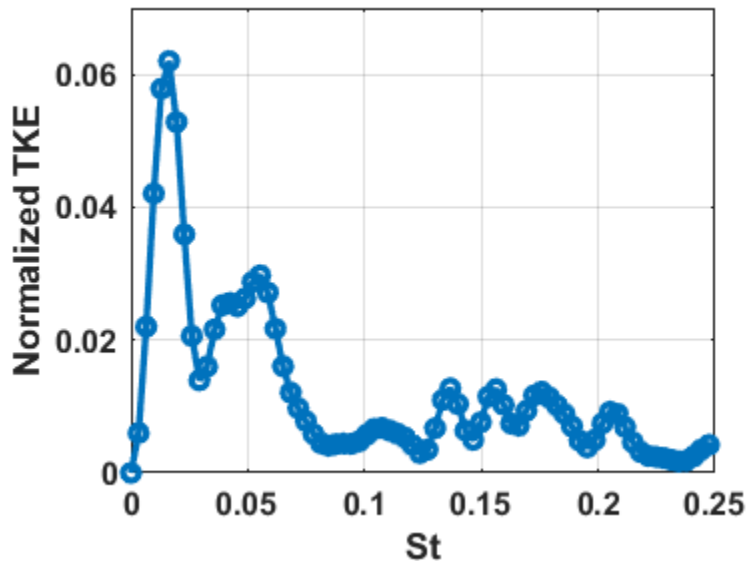


Figure 28: Normalized TKE for vertical velocity aft of the obstacle along $x=0\text{m}$ plane.

For the $St \in (0,0.03]$ bin, the first two modes account for 69% of the total TKE. These modes are plotted in Figure 29 and Figure 30. From Figure 29, it is not immediately clear which flow behavior is captured by mode #1. A time lapse of longitudinal velocity contour is shown in Figure 31. At $t = 5\text{s}$, there is a negative vertical velocity region immediately aft of the cube, evident by the purple oval region seen in the Figure. Slightly further downstream, a positive

vertical velocity region, indicated by green shading. As time passes, a cyclic alternation in the spatial location of the negative (purple) and positive (green) velocity zones is apparent suggesting shedding of some type. The contour plot of mode #1 in Figure 29 indicates this flow behavior. This phenomenon contributes to 36% of the TKE in the $St \in (0,0.03]$ bin. Mode #2, plotted in Figure 30, seems to capture the interaction between the flow associated with the aft recirculation and the top shear layer. This interaction contributes to 30% of the TKE in the $St \in (0,0.03]$ bin.

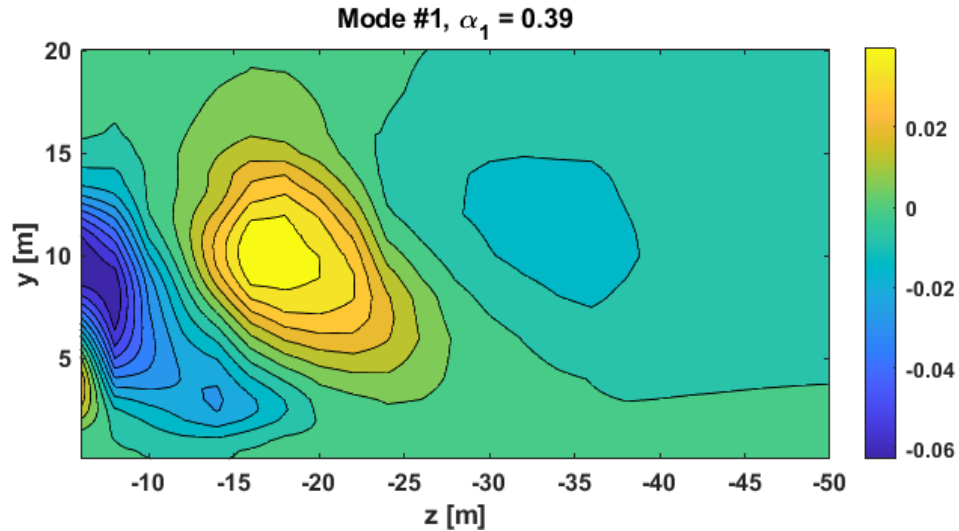


Figure 29: Mode #1 from POD analysis of vertical velocity data aft of the obstacle along $x=0m$ plane in $St \in (0,0.03]$ bin.

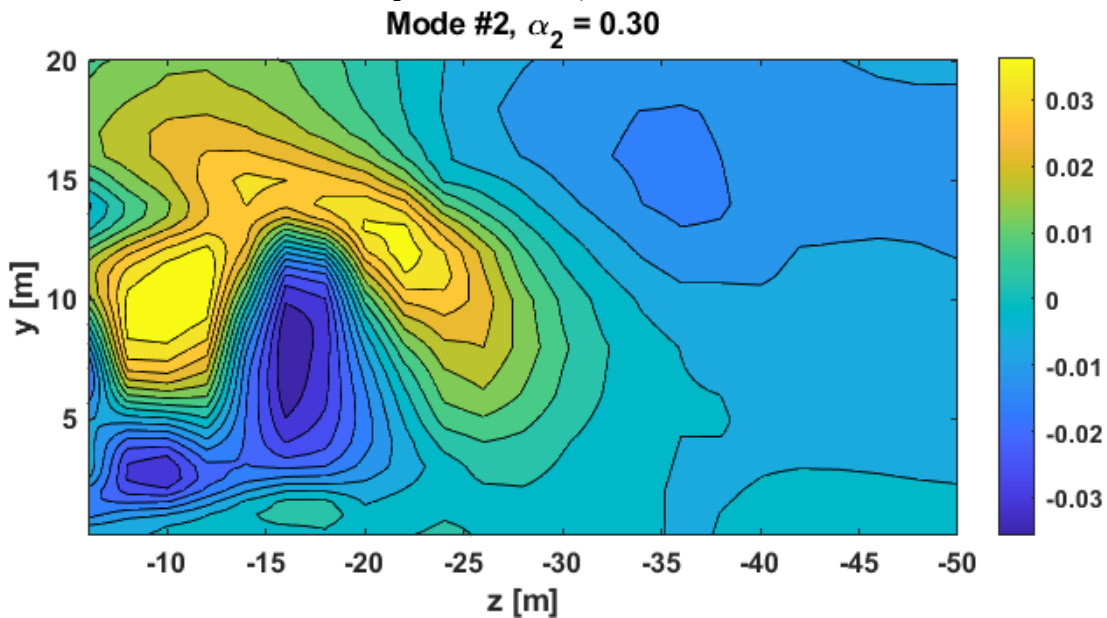
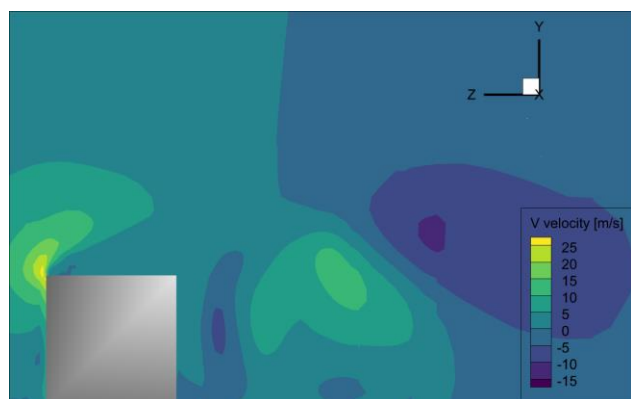
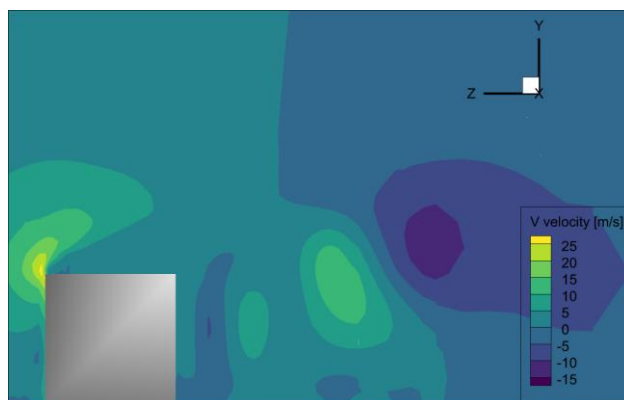
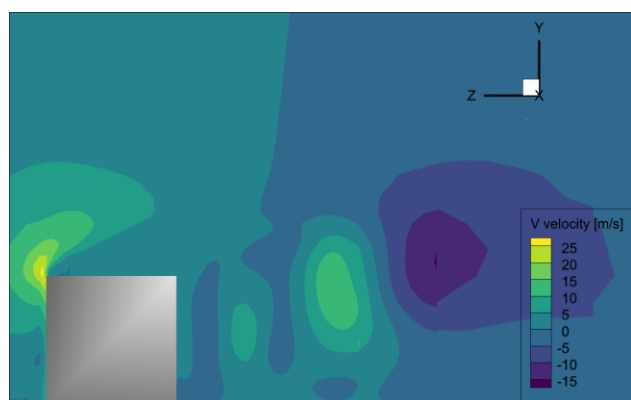
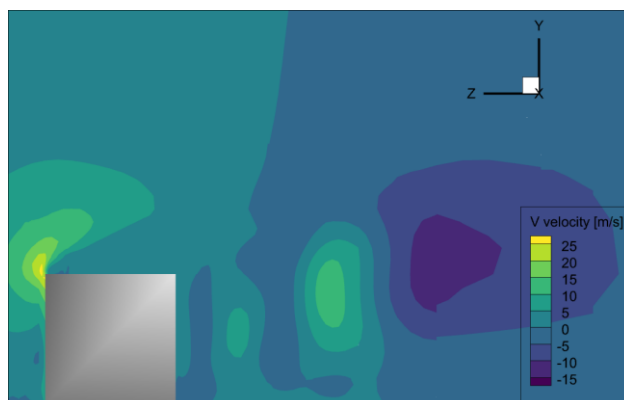


Figure 30: Mode #2 from POD analysis of vertical velocity data aft of the obstacle along $x=0m$ plane in $St \in (0,0.03]$ bin.

(a) $t=5s$ (b) $t=5.2s$ (c) $t=5.4s$ (d) $t=5.6s$ (e) $t=5.8s$ (f) $t=6s$

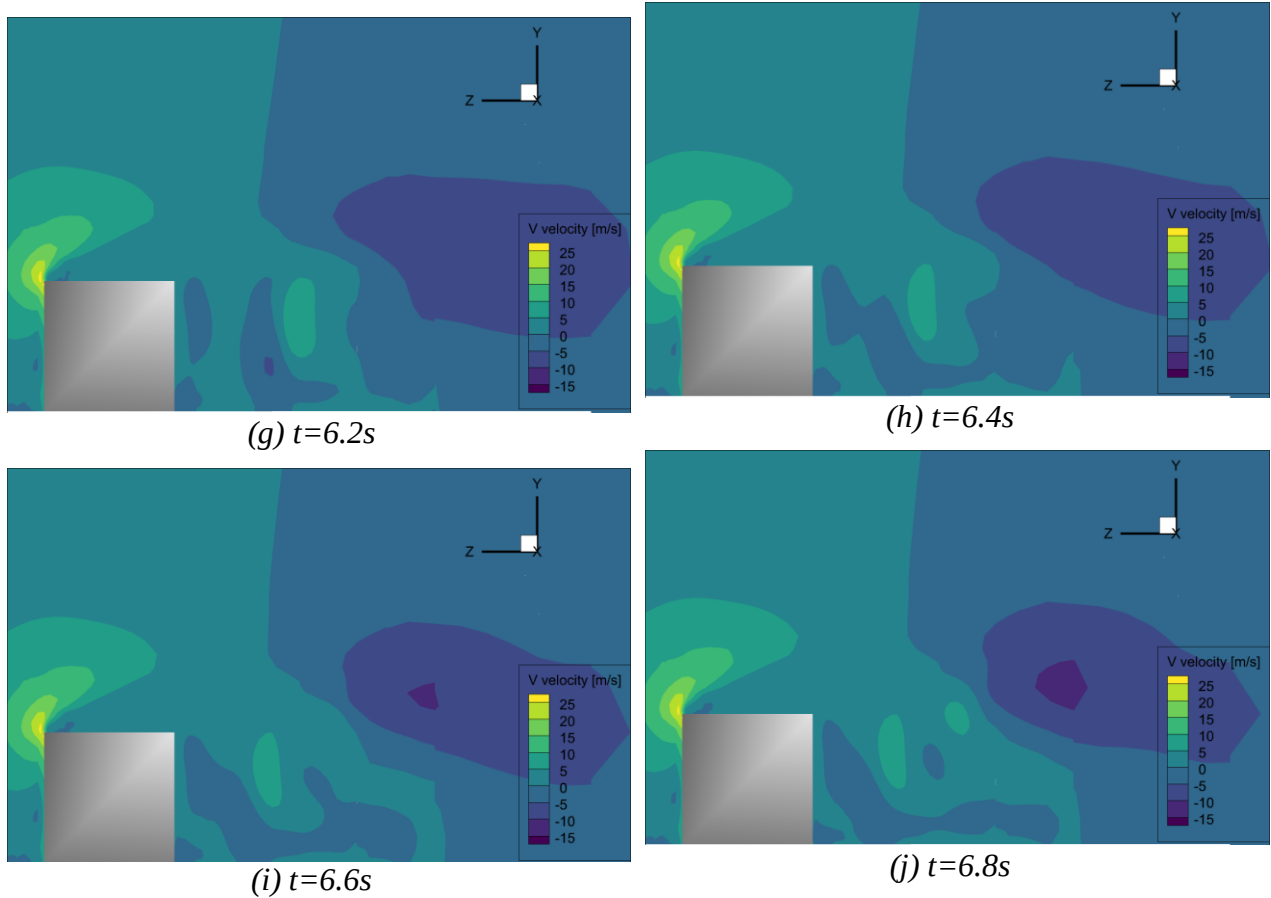


Figure 31: Time-lapse of vertical velocity contour along $x=0m$ plane.

For the $St \in (0.03, 0.065]$ bin, it was found mode #1 contributed 36% to the total TKE and exhibited a similar structure to the dominant mode from the previous bin shown in Figure 29.

Characterization Along $y=5m$ Plane: Longitudinal Velocity

The midplane shown in Figure 7(b) is considered in this section. The normalized TKE values obtained using the cross-spectral density matrix from Eq. (14) are shown in Figure 32. The most energetic dynamic flow features occur in the $St \in (0.065, 0.1]$ range. A filtered data matrix isolating flow features in this bin was generated and examined using POD. The first two modes contribute the most to the overall TKE in that bin. Mode #1 is plotted in Figure 33. This mode captures the characteristic bistability of flow observed aft of back steps where flow switches intermittently between portside and starboard locations [54]. This flow bistability contributes to 38% of the TKE in the $St \in (0.065, 0.1]$ bin. Mode #2 displays the onset of the bistability immediately aft of the cube in Figure 34, where the larger alternating flow features seen in mode #1 are broken up into contributions from the shear layer on either side obstacle and associated recirculation regions. Mode #2 contributes to 27% of the TKE in the $St \in (0.065, 0.1]$ bin. Note that Zhu et al. [54] identify the bistable flow feature in the $St \in (0, 0.06]$ bin in their experimental study, which considered three headwinds (15.2, 45.7 and 61 m/s) over $1/90^{\text{th}}$ scale model of the SFS2 ship geometry.

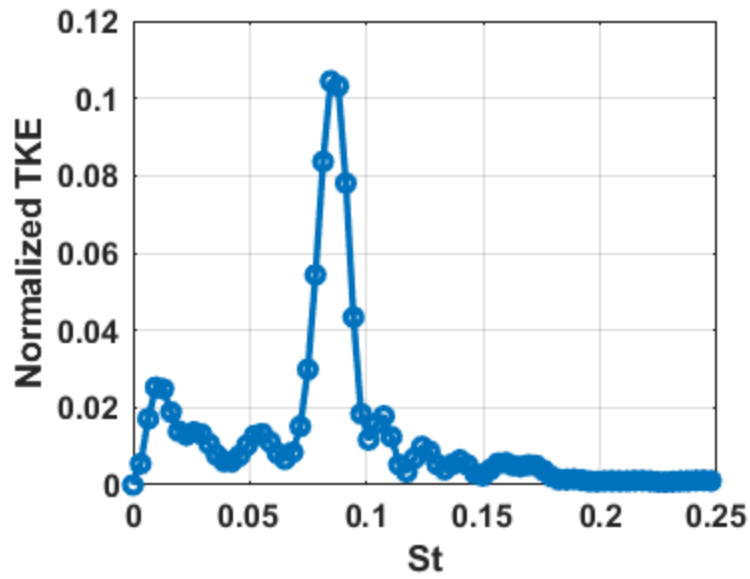


Figure 32: Normalized TKE for longitudinal velocity aft of the obstacle along $y=5\text{m}$ plane.
Mode #1, $\alpha_1 = 0.38$

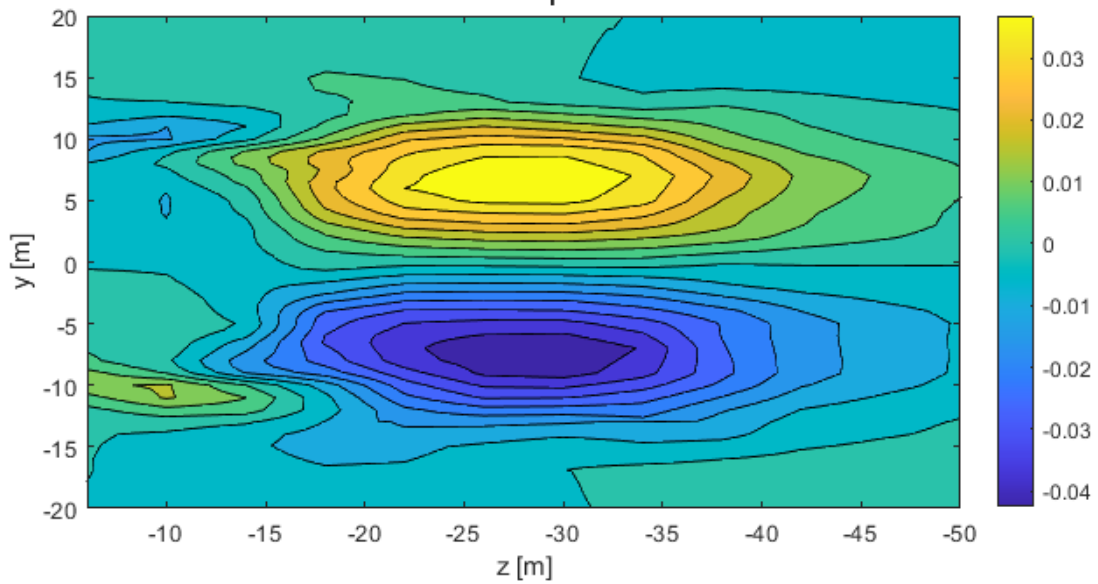


Figure 33: Mode #1 from POD analysis of longitudinal velocity data aft of the obstacle along $y=5\text{m}$ plane in $St \in (0.065, 0.1]$ bin.

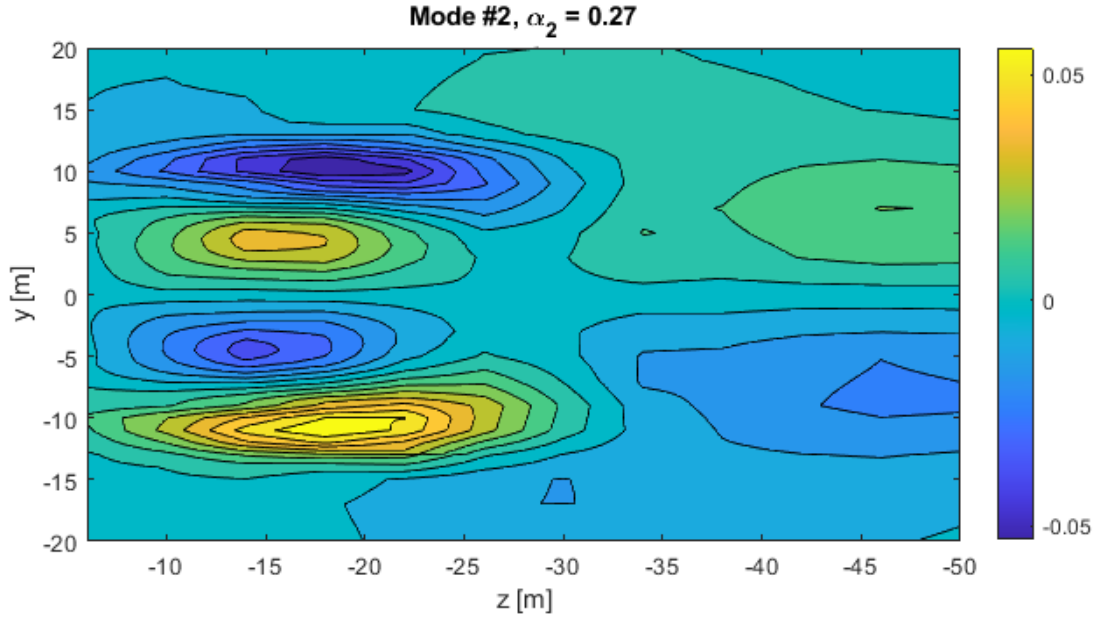


Figure 34: Mode #2 from POD analysis of longitudinal velocity data aft of the obstacle along $y=5\text{m}$ plane in $St \in (0.065, 0.1]$ bin.

Characterization Along $y=5\text{m}$ Plane: Vertical Velocity

For the vertical velocity, the same frequency bin of $St \in (0.065, 0.1]$ and bistable flow feature are identified. Results are not shown here for brevity.

It is important to note that the energetic flow features identified in the results above are all present in low frequency bins that can directly influence aircraft flight dynamics and handling qualities.

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 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;
- Quasi-static 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 (nondimensionalized by rotor radius R) 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:

$$\begin{aligned}
C_T &= C_T^* - \frac{Nca}{4\pi^2} \int_0^{2\pi} \int_0^1 v_{vortex}(r, \psi)(r + \mu \sin \psi) dr d\psi, \\
\beta_0 &= \beta_0^* - \frac{ca}{4\pi^2 \omega^2 I_\beta} \int_0^{2\pi} \int_0^1 v_{vortex}(r, \psi)(r^2 + \mu r \sin \psi) dr d\psi, \\
\beta_{1s} &= \beta_{1s}^* + \frac{ca}{2\pi^2(\omega^2 - 1)I_\beta} \int_0^{2\pi} \int_0^1 v_{vortex}(r, \psi)(r^2 \sin \psi + \mu r \sin^2 \psi) dr d\psi, \\
\beta_{1c} &= \beta_{1c}^* + \frac{ca}{2\pi^2(\omega^2 - 1)I_\beta} \int_0^{2\pi} \int_0^1 v_{vortex}(r, \psi)(r^2 \cos \psi + \mu r \cos \psi \sin \psi) dr d\psi,
\end{aligned} \tag{17}$$

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. (17).

Rotor Fundamental Response

Earlier, 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. (17) and enables the computation of fundamental rotor response to the airwake velocities associated with the arch vortex. For the fundamental response analysis, we consider rotors representative of four helicopters as summarized in Table 2. The expressions in Eq. (17) are evaluated using the rotor properties from Table 2 and the arch vortex model vertical velocity predictions obtained using Eq. (7). 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 shown in Figure 6.

Table 2: Rotor properties considered in fundamental response analysis

Vehicle	Number of blades	Chord [ft]	Radius [ft]	Rotation speed [rad/s]	GW [lbs]	Ibeta [slug-ft ²]
MQ-8C Fire scout (Bell 407)	4	0.9	17.5	43.25	5400	143.8
UH-60	4	1.73	26.83	27	16500	1512.6
V-22	3	2.09	19	41.57	39500	721.6
CH-53E	7	2.44	39.5	18.53	60000	6744.7

The magnitude of the arch vortex influence on the thrust coefficient (C_T) and longitudinal disk tilt (β_{1c}) on different rotors is depicted in Figure 35 and Figure 36 for hover ($\mu = 0$), respectively. The change in lateral disk tilt (β_{1s}) is negligible due to symmetry in the arch vortex and rotor positions and is thus not shown here. Points that lie furthest from the origin indicate the strongest influence on the Figures. At location #1, the influence of the arch vortex on the thrust coefficient of 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. Note that we obtain the greatest longitudinal flapping response at location #2 for the CH-53E rotor in Figure 36. This is due to the size and position of the rotor relative to the arch vortex. 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 37 and Figure 38, respectively. From Figure 38(b), the fore part of the CH-53E rotor experiences an upwash while the aft part experiences a downwash due to the arch vortex. The combined effect produces the large rotor disk tilt. Note also from the contour plots that seasonable agreement in velocity predictions is noted with CGE/VorTran-M predictions, with the largest discrepancies noted for the vertical velocity predictions, as was noted previously as well.

These results indicate that rotor properties (size, number of blades etc.) and position relative to the flow features are both important factors in assessing the influence of airwake flow features on rotor responses.

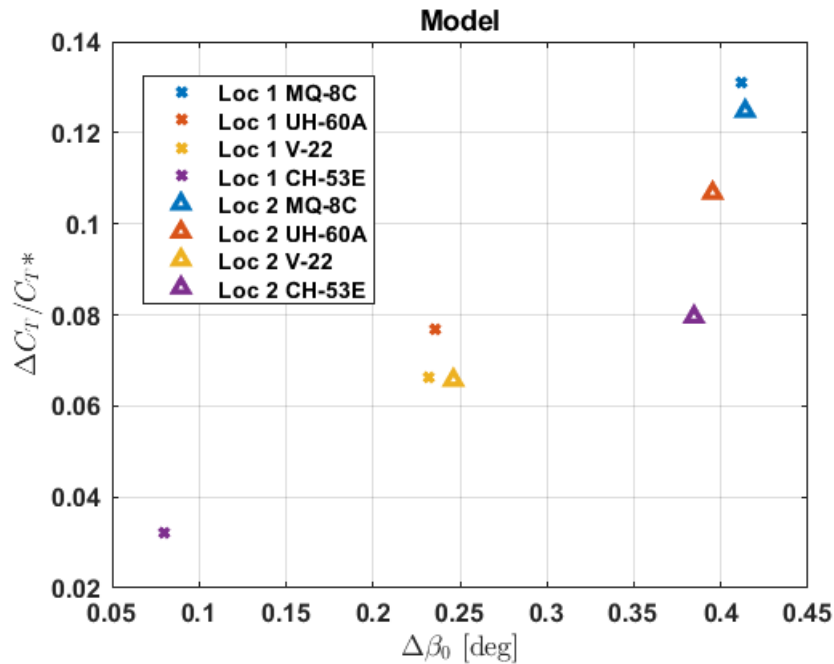


Figure 35: Influence of arch vortex on rotor fundamental response; $C_T^* = W / \rho (\pi R)^2 (\Omega R)^2$, $\Delta C_T = C_T - C_T^*$, $\Delta\beta_0 = \beta_0 - \beta_0^*$.

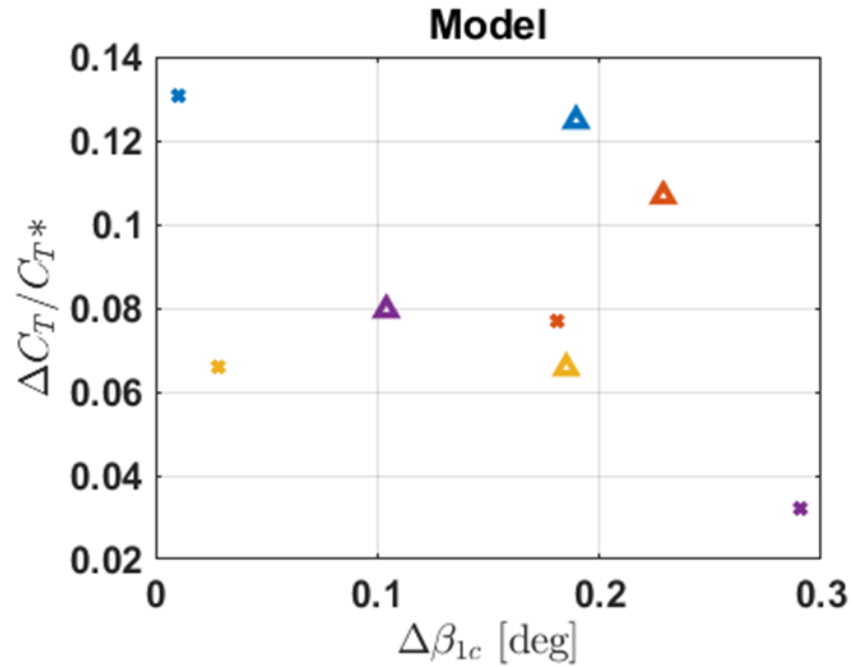


Figure 36: Influence of arch vortex on rotor longitudinal disk tilt; $C_T^* = W / \rho(\pi R)^2(\Omega R)^2$,
 $\Delta C_T = C_T - C_T^*$, $\Delta\beta_{1c} = \beta_{1c} - \beta_{1c}^*$.

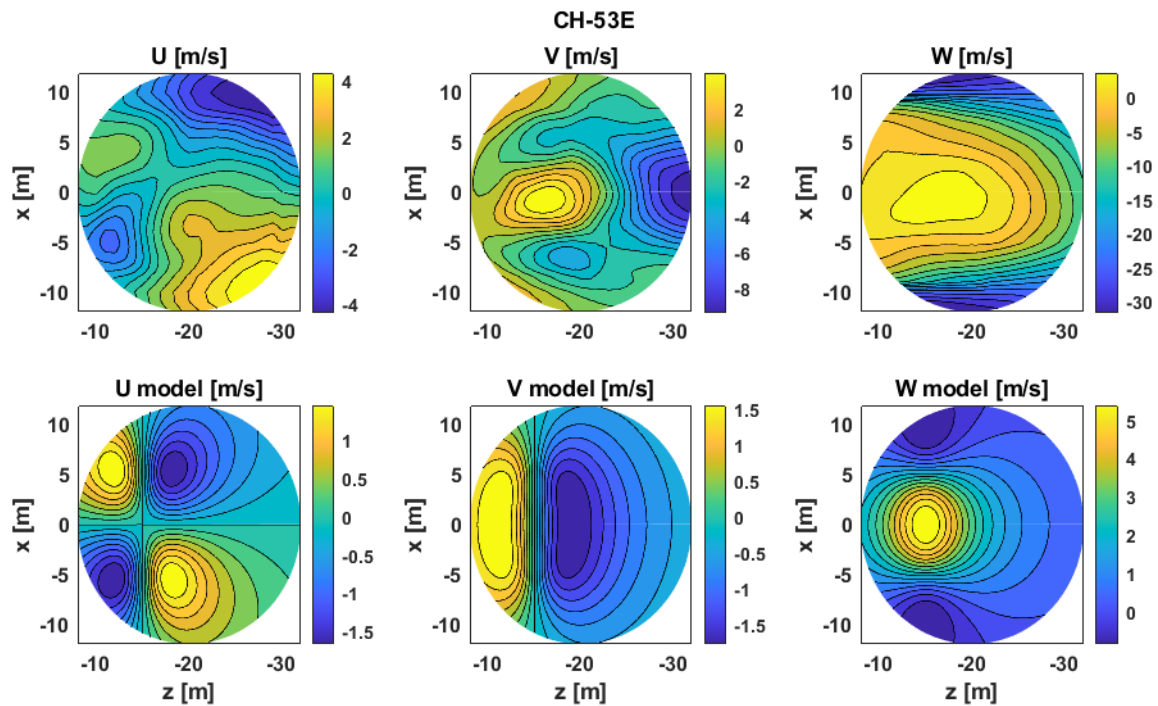
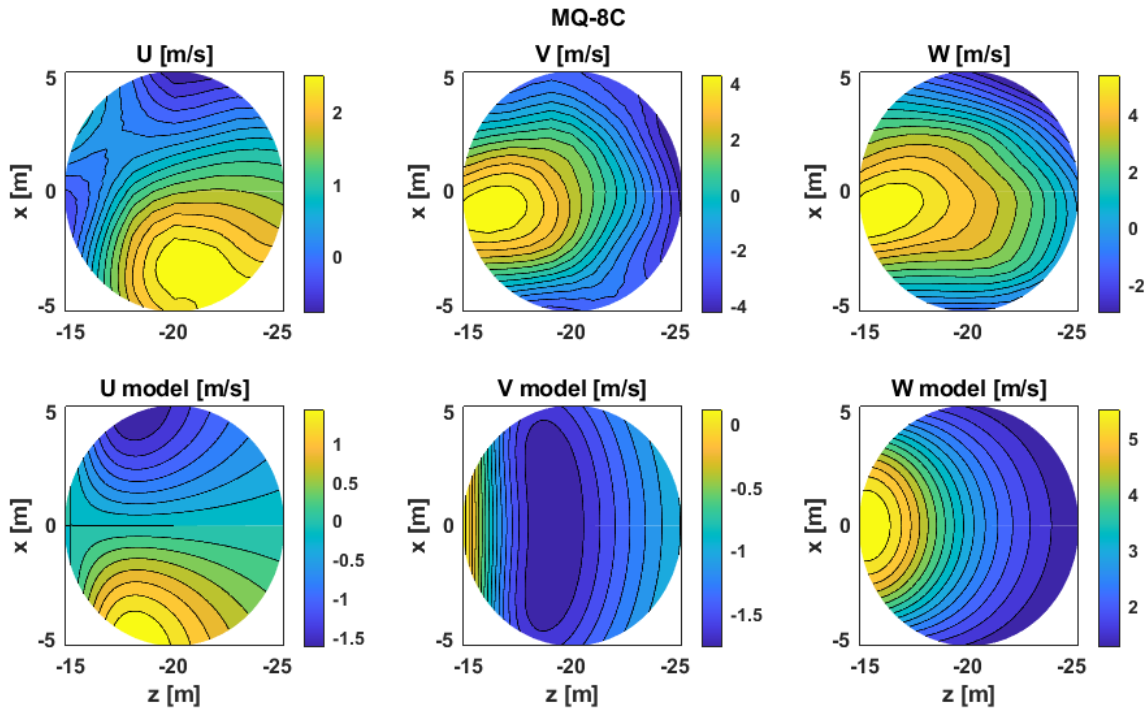
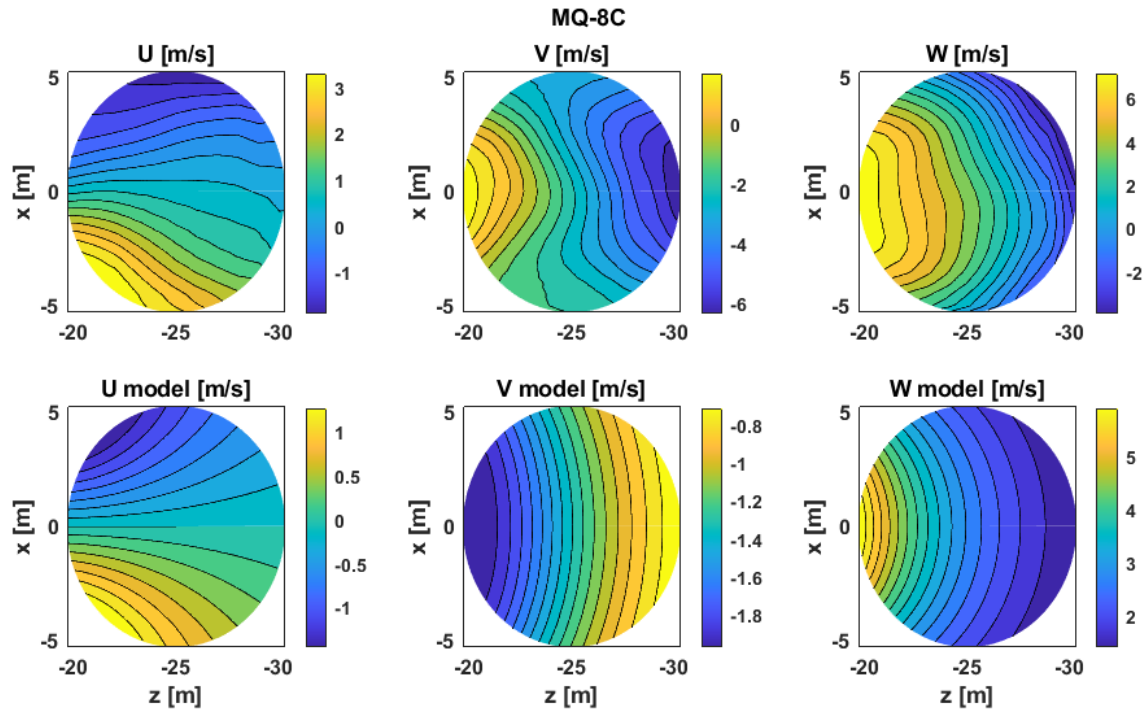
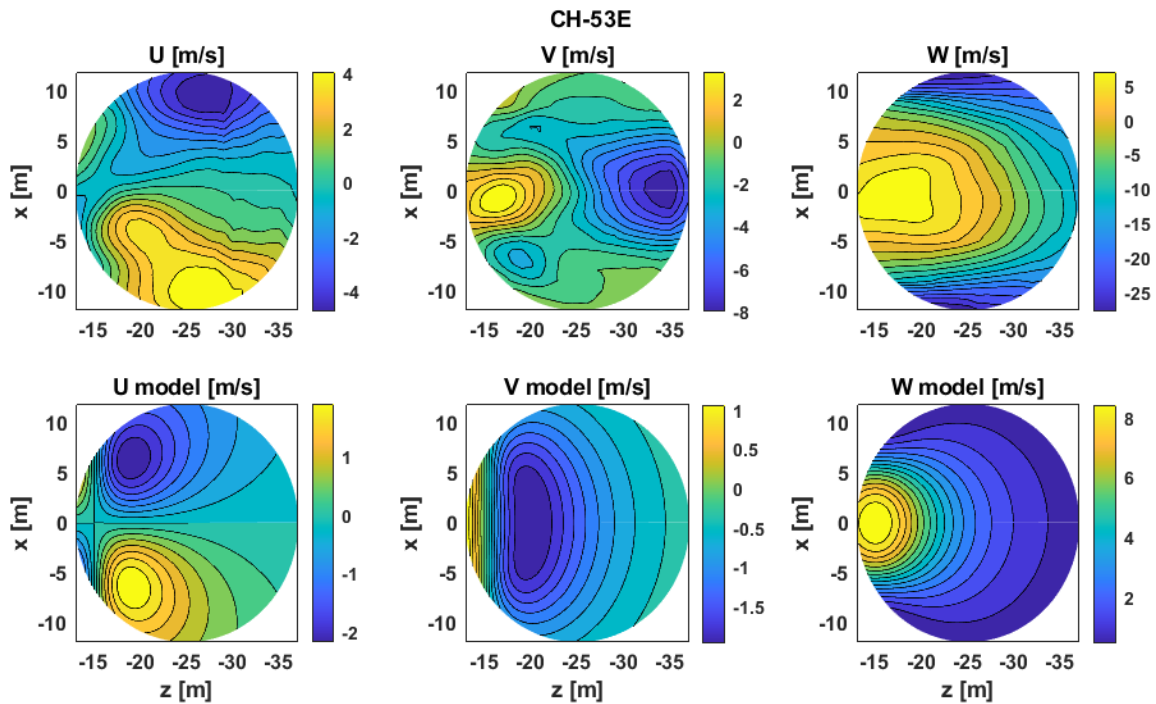


Figure 37: Contours of airwake velocity components over MQ-8C and CH-53E rotor centers at location #1 where $[x,y,z] = [0, 8, -20]$ m.



(a)



(b)

Figure 38: Contours of airwake velocity components over MQ-8C and CH-53E rotor centers at location #2 where $[x,y,z] = [0, 6, -25]$ m.

Conclusions

Work to date has focused on investigating the type of disturbance fields experienced by Naval aviators, and how to define the relevant primary flow structures and time scales. Approaches for developing simplified representations have been investigated, and as the effort progresses, we will commence developing representative surrogate flow fields that will be used in the flight simulations described above. Recent work has continued investigations into how to parameterize the wake structures and how to use simpler models to represent them. Flight dynamics model development and quantification of a rotorcraft's fundamental response to interactions with wake structures has commenced.

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