

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

Quarterly Status Report 1

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## **Project 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 **Error! Reference source not found.**). 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) 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 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].

### **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).

## **Summary of Work Conducted During Reporting Period**

During this reporting period a kickoff briefing was held remotely with Navy personnel, and a copy of the kickoff briefing slides and attendee list are included in Appendix A. Work has commenced investigating the type of disturbance fields experienced by Naval aviators, and how to define the relevant primary flow structures and time scales. To date, work has focused on the bluff type flows associated with buildings/hangars and small-deck ships, and we are starting to expand this investigation into more discrete structures such as deck-edge vortices that occur on flat-top ships.

## **Disturbance Field Characterization**

### *Flow Characteristics*

Properties of flow over two-dimensional obstacles are described first, followed by a description of characteristics over 3D obstacles. Although the direction of the incoming wind plays an important role on flow characteristics [9-11], the discussion that follows will focus on headwind conditions to aid in understanding. Similarly, we initially discuss 2D flows for simplicity since they're representative of the flow immediately downstream of, and in the center of, the disturbance generator.

#### Backward-Facing Step (2D)

Figure 2 illustrates the general flow features associated with a backward-facing step [12], where an unstable shear layer is formed when the upstream boundary layer separates at the sharp corner [13, 14]. This shear layer consists of concentrated vorticities with fluctuating velocity gradients that become increasingly more turbulent as the shear layer propagates downstream with increasing curvature towards the reattachment zone, where part of it is deflected upstream

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towards the recirculation zone (where the pressure is lower), and part of it is entrained downstream up to as much as 50 step heights [13].

In the recirculation zone, a primary larger “bubble” can be identified, where flow velocities directed upstream can reach up to 20% of freestream velocities, and where negative skin-friction coefficients have been measured in tests [13]. A secondary smaller recirculation zone can also result when 3D effects due to the presence of side walls are accounted for – see discussion below and in [15, 16].

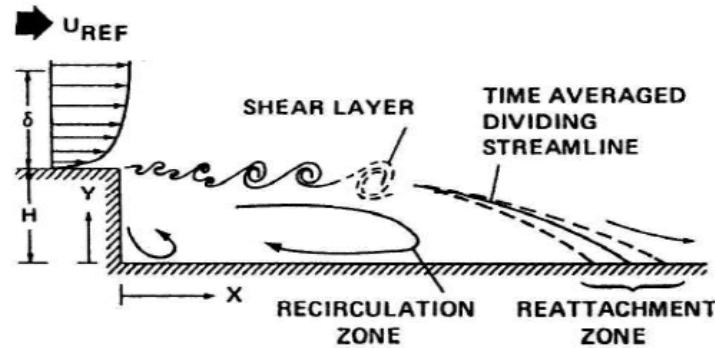


Figure 2: Flow topology over backward-facing step [4].

Flow in the reattachment zone is highly unsteady with coherent structures with length scales at least as large as the step height passing through this region [13, 17]. Coherent structures are large scale vortex structures that conserve their spatial features for prolonged durations. The location where the shear layer impinges on the wall fluctuates, shifting the reattachment zone upstream and downstream at low frequency [13, 14, 18, 19], with the primary recirculation bubble shrinking and expanding accordingly. Driver et al [12] suggest that this “flapping” motion results when part of the shear layer having greater momentum entrains more of the flow downstream, resulting in less flow being diverted towards the recirculation region. This causes the recirculation region to shrink and increases the shear layer curvature, which, in turn, increases the adverse pressure gradient in the reattachment zone, forcing flow back into the recirculation region. The amplitude of this flapping motion is estimated to be approximately 20% of the shear layer width  $b$ , which is given by

$$b = \Delta U / (d\bar{u}/dy)_{max}, \quad (1)$$

where  $U$  is the mean velocity in the stream wise direction,  $\bar{u}$  is the streamwise velocity fluctuation, and the  $y$  coordinate is as defined in Figure 2 [12]. Driver et al further note that this low frequency motion does not have a strong impact on flow turbulence [12]. It should be noted that there is no consensus on the origin of the flapping motion in literature, for example see [17].

The mean reattachment length  $x_R$ , which represents the point of zero skin friction, is generally used to characterize the reattachment zone and can vary from  $4.9H$  to  $8.2H$ , where  $H$  is the step height, depending on the following parameters:

- a) Reynolds number of the initial boundary layer,
- b) boundary layer thickness,
- c) free stream turbulence, and
- d) blockage effects (for wind tunnel tests) [13].

In general,  $x_R$  is sensitive to the boundary layer Reynolds number only in the laminar and transition regimes (see Figure 3), and the effect of boundary layer thickness  $\delta$  is noted to be more pronounced when  $\delta/H \ll 1$  [13]. Eaton and Johnston [13] suggest that  $x_R$  decreases with high levels of freestream turbulence, and that its effect would likely be dependent on the spectrum of the turbulence.

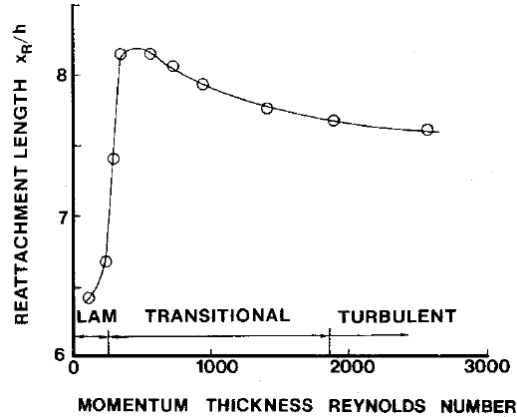


Figure 3: Influence of Reynolds number on reattachment length [13].

Eaton and Johnston [13] further show that maximum turbulence intensity  $I$ , defined as the ratio of root-mean-square of turbulent velocity fluctuations to mean absolute velocity

$$I = \frac{\bar{u}}{U_0}, \quad (2)$$

tends to be close to  $I = 20\%$ , and is typically observed approximately  $1H$  upstream of the mean reattachment point. Beyond  $1H$ , the maximum turbulence intensity decays rapidly.

Vortex shedding is characterized by the Strouhal number which is defined as

$$St = \frac{fb}{U}, \quad (3)$$

where  $f$  is the vortex shedding frequency and  $b$  is the characteristic length. Through spectral analysis of the pressure fluctuations at two streamwise locations  $x/H = 5.5$  and  $x/H = 8.0$ , Driver et al. [12] identify a dominant frequency of  $St = 0.2$ , which is comparable to the characteristic frequency noted in the spanwise vortical structures of free shear layers, and is consistent with shedding from a flat plate aligned perpendicular to the flow [20].

#### Rectangular Prism (2D)

In 2D flow over a rectangular prism, free shear layers are shed from the sharp edges of the cross-section as depicted in Figure 4 [21], where streamlines over four rectangular prisms with different width-to-length aspect ratios are shown. It is evident that aspect ratio influences the mean reattachment length, and for aspect ratios 1:3 and 1:4, the mean flow reattaches to the lateral sides of the rectangle. The resulting mean (time averaged) flow features are also symmetric. The Strouhal number for vortices shed by rectangular prisms can vary from 0.1 to 0.18 depending on the aspect ratio and Reynolds number [22].

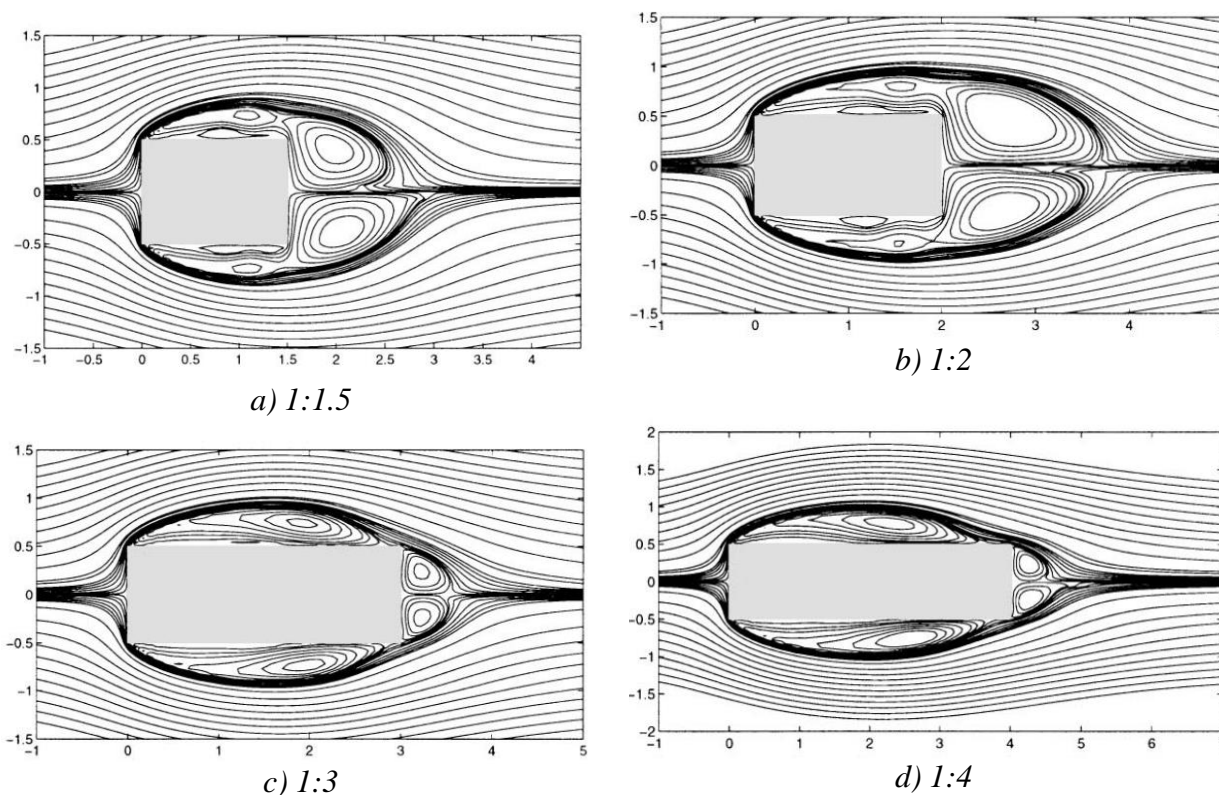


Figure 4: Streamline of mean flow around rectangular prisms with different aspect ratios [21].

#### Surface-Mounted Cuboid (3D)

Flow over 3D obstacles, such as cuboids, introduces additional complexity relative to the 2D case as end and side wall effects become important [23, 24]. Flow features around a surface-mounted cuboid are depicted in Figure 5 and Figure 6 [23]. Upstream of the obstacle, horseshoe vortices form that extend over the sides of the obstacle and interact with the downstream separation region, resulting in high flow unsteadiness [25]. An arch vortex forms on the leeward side of the obstacle, and flow detaches at the top edge of the wind-facing surface of the obstacle and reattaches downstream of the arch vortex. The mean reattachment length in 3D is shorter than that noted for 2D backward facing step due to side wall effects. Note from Figure 5 that time-averaged flow features are symmetric.

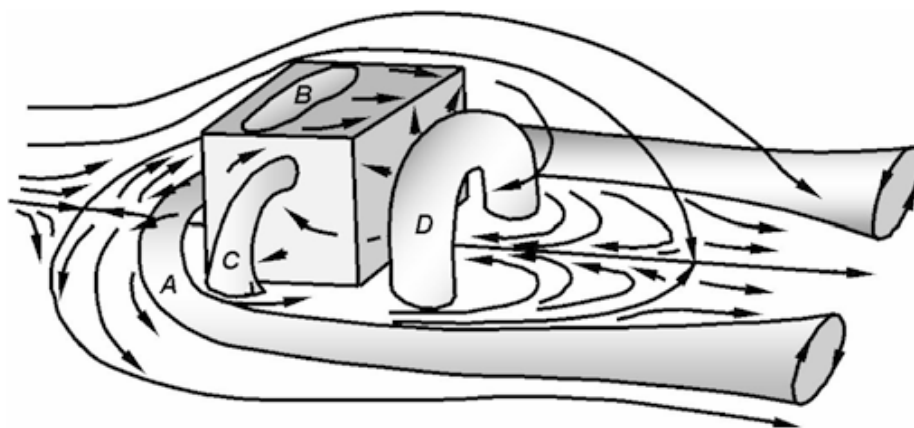


Figure 5: Schematic of principal flow features around surface-mounted obstacle [23].

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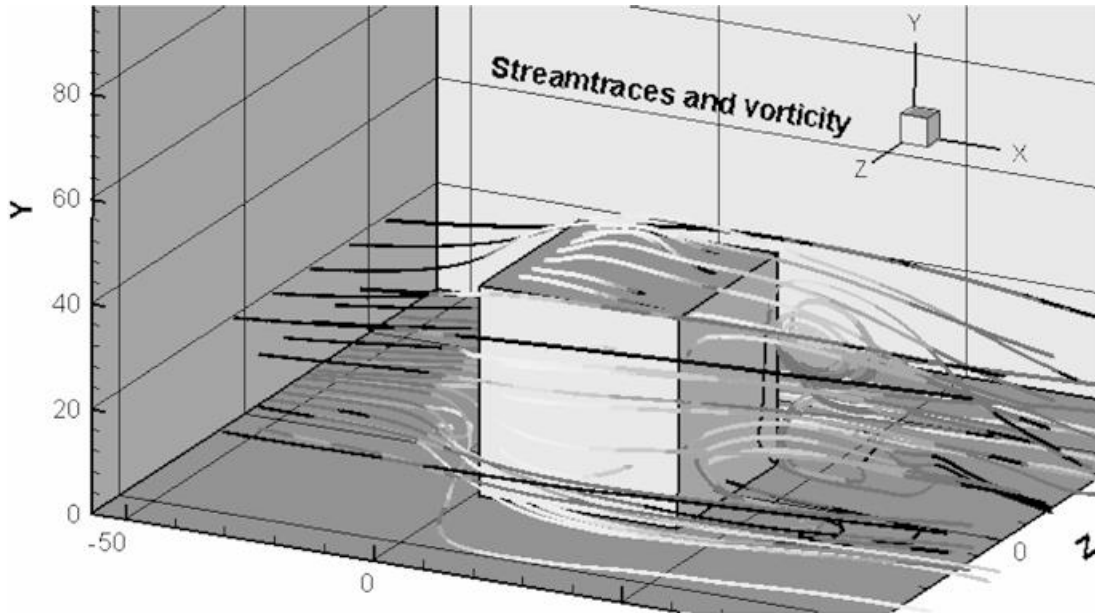


Figure 6: Perspective view of streamlines around surface-mounted obstacle [23].

Similar flow features are noted with 3D rectangular prisms [26], though they are sensitive to aspect ratio [27]. If the height is less than the length and width, the flow reattaches on the top surface of the prism, and up to three recirculation regions are observed, as shown in Figure 7 [26]. The location of the reattachment point on the top surface and behind the prism varies in the spanwise direction as depicted in Figure 8 [26]. Herry [27] notes that the location of the reattachment point is sensitive to the obstacle length-to-height aspect ratio, width-to-height aspect ratio, and Reynolds number. There is a minimum Reynolds number  $Re_c$  above which flow features become independent of Reynolds number for bluff bodies with sharp edges [10, 28, 29], however, a general rule for obtaining  $Re_c$  based on geometrical properties does not seem to have been established [28].

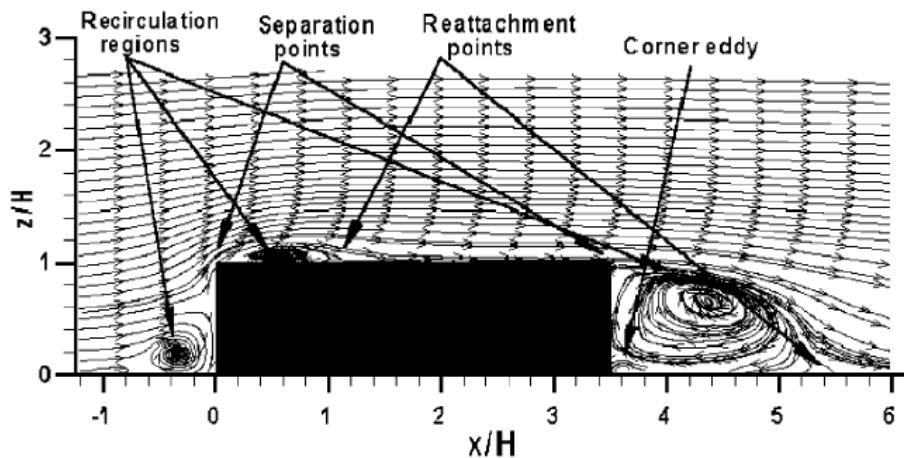
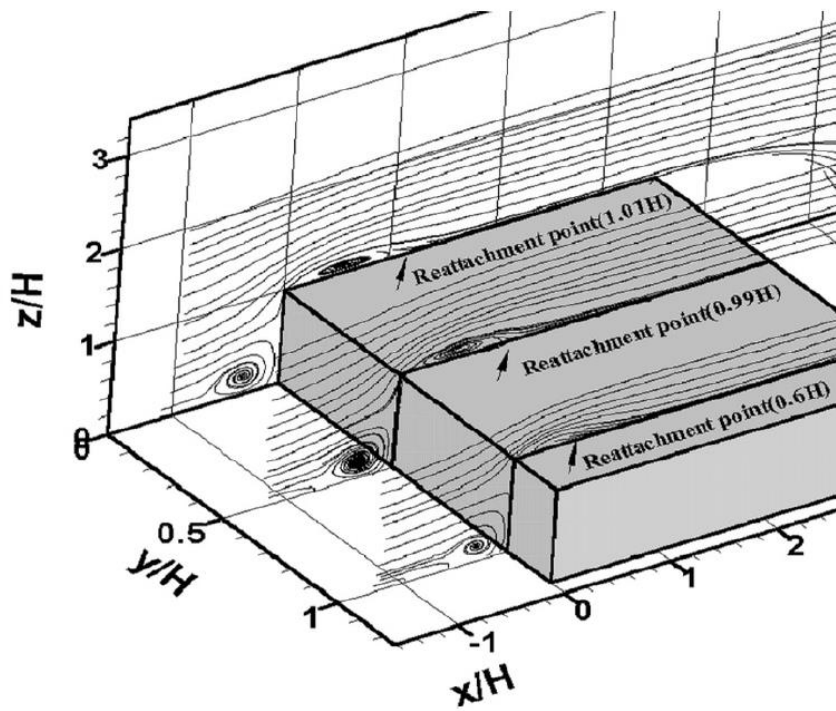
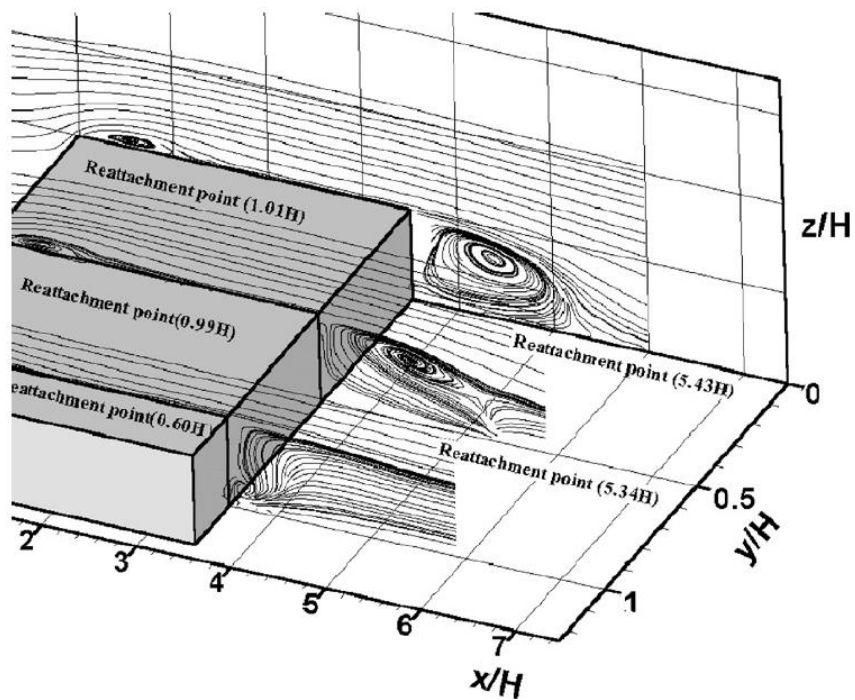


Figure 7: PIV derived streamlines at center plane around surface-mounted obstacle [26].



(a)



(b)

Figure 8: Streamlines of flow over surface mounted obstacle seen from (a) windward and (b) leeward directions [26].

An important parameter used to quantify flow turbulence is the turbulent kinetic energy (TKE) defined as [26]

$$TKE = \frac{1}{2}(\overline{u^2} + \overline{v^2} + \overline{w^2}), \quad (4)$$

where,  $\bar{u}, \bar{v}, \bar{w}$  represent fluctuating streamwise, spanwise and vertical velocity components. TKE can be related to turbulence intensity, introduced previously, as:

$$I = \sqrt{\frac{2}{3}TKE} \quad (5)$$

Kim et al. [26] observed peak TKE levels on the top surface of a  $3.5H$  long rectangular prism at  $x \approx 0.5H$ , see Figure 9. Becker et al. [10], on the other hand, examined flow over a rectangular prism with a shorter length of  $0.25H$  and observe peak turbulence levels at  $x = 3H$ , as depicted in Figure 10, demonstrating the influence of aspect ratio on flow characteristics. Their spectral analysis further indicates dominant frequencies at  $St_H = 0.15$ , with little sensitivity to Reynolds number and the width-to-height aspect ratios (1:2, 1:3, 1:4 were considered) [10]. Note that this Strouhal number is higher than  $St_H = 0.104$  noted for flow over cubes [25]. The subscript ‘‘H’’ indicates that the obstacle height was used as characteristic length in computing the Strouhal numbers, see Eq. (3).

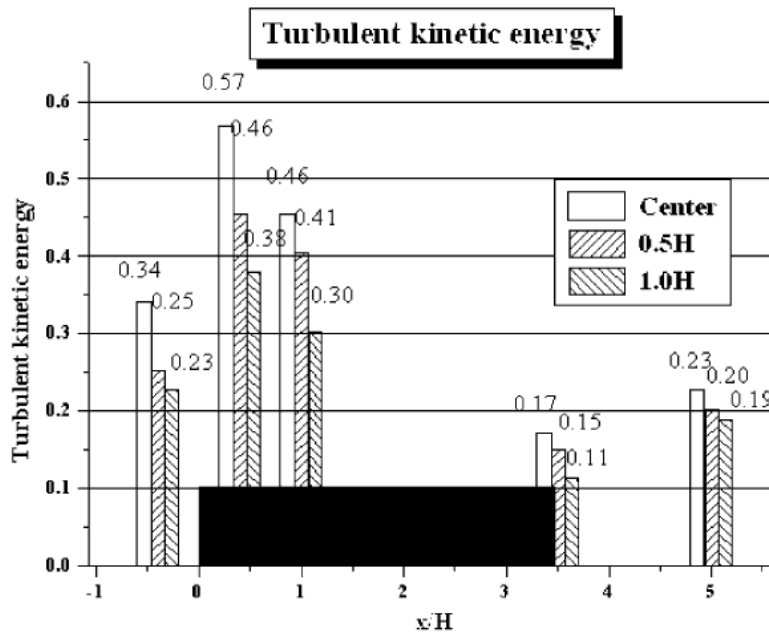


Figure 9: Turbulent kinetic energy peaks at different locations for flow over a 3D rectangular prism from Ref. [26] (boundary layer thickness of  $\delta = 0.06H$  and Reynolds number (based on step height) of  $7.9 \times 10^3$ )

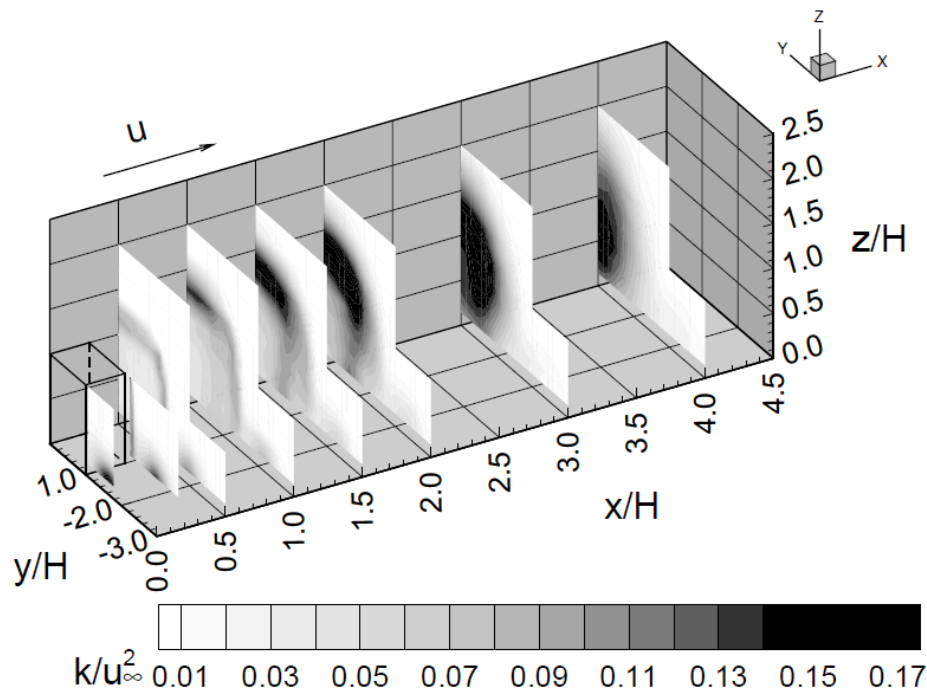


Figure 10: Turbulent kinetic energy at different locations for flow over a 3D rectangular prism from Ref. [10].

#### Double-Backward Facing Step (3D)

The double-backward facing step geometry, depicted in Figure 11 along with prevalent flow features [30], closely matches the aft region of typical small-deck aviation ship geometries and is thus of particular interest. Tinney and Ukeiley [30] derived the flow features in the figure using both PIV and oil-flow visualizations at  $Re = 9000$  for the ship geometry shown in Figure 12. The flow features in Figure 11 are similar to those for flow over a surface mounted cube shown in Figure 5, with some notable differences. In the flow aligned case, the upstream horseshoe vortex seen in Figure 5 is no longer present in Figure 11 due to flow reattaching on the walls of the structure before the first step. Streak lines that start along the edges of the ship structure from the nose curl up into vortex tubes, denoted as “wing vortex” in Figure 11, due to pressure gradients between the side and top surfaces of the structure and interact with flow downstream of the reattachment region to produce counter-rotating vortex tubes on both sides of the streamsurface bifurcation point on the figure.

Although Figure 11 depicts a symmetric upside-down arch vortex aft of the first step, this structure is unsteady and at any instant in time is asymmetric, see Figure 13 from [27]. This is a consequence of bi-stability of the flow, which causes the resulting asymmetric flow features to switch intermittently between portside and starboard locations. The influence of this asymmetry on helicopter-shipboard operations remains to be examined.

Tinney and Ukeiley [30] observe peak longitudinal turbulence intensity near the recirculation zone at  $1H \leq x \leq 2H$  downstream of the first step (see Figure 14a) and peak vertical turbulence intensity closer to the reattachment zone in the  $2H \leq x < 4H$  region (see Figure 14b). Turbulent kinetic energy is dominated by longitudinal velocity fluctuations, and peak TKE is observed in  $1H \leq x < 2.5H$  region in Figure 14d. Note that the TKE was computed using only longitudinal

$\bar{u}$  and vertical  $\bar{v}$  components. The longitudinal and vertical turbulent intensities in the figure are noted to be greater than those observed with 2D obstacles [30]. The dominant frequency was characterized by a Strouhal number of  $St_H = 0.17$  [30].

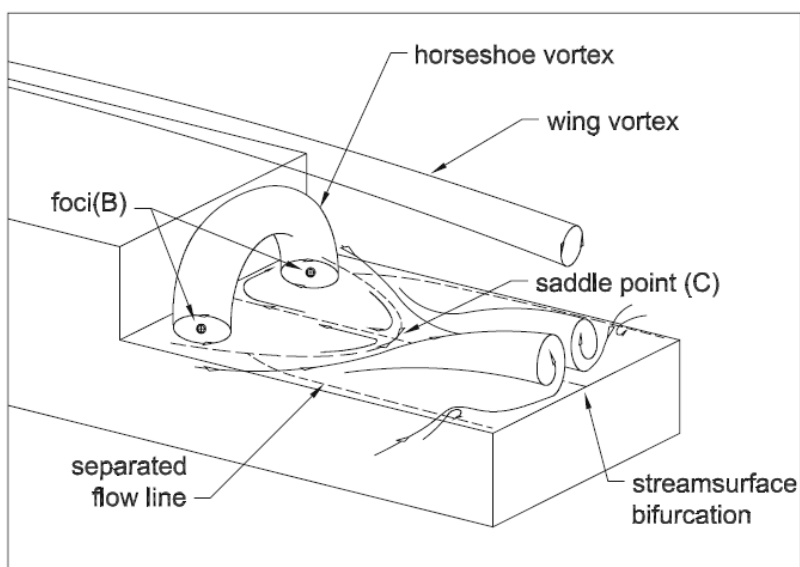


Figure 11: Flow feature for a 3D double-backward facing step [30].

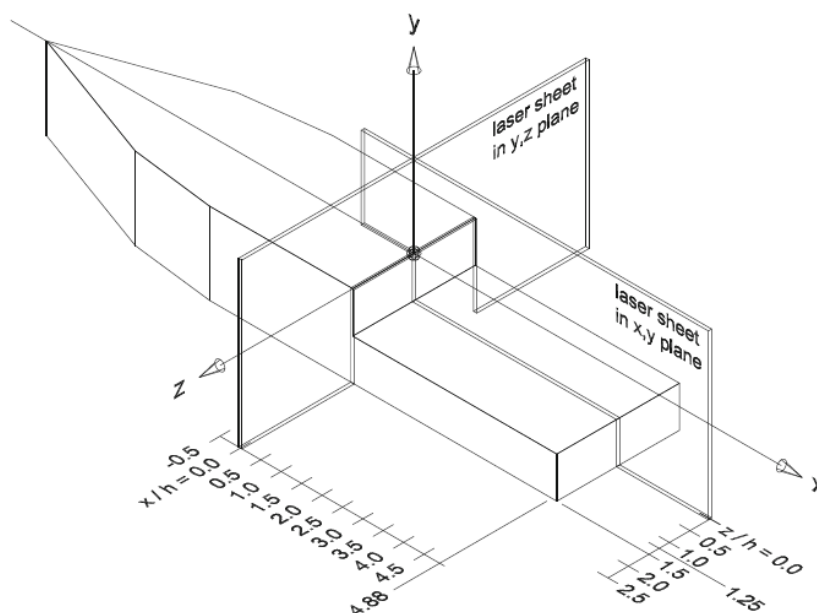


Figure 12: Ship geometry used to derive flow features for a 3D double-backward facing step [30].

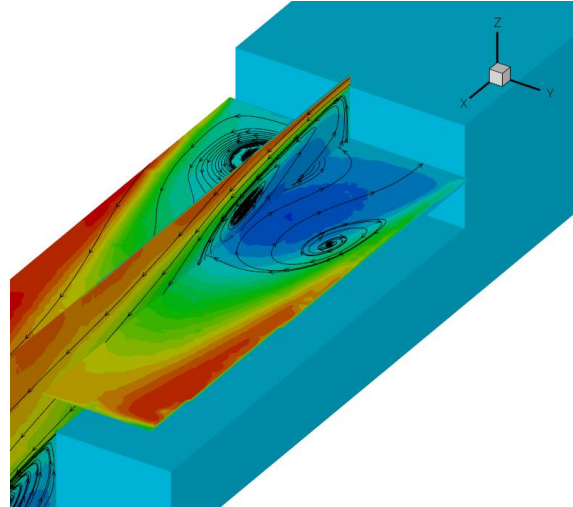


Figure 13: Asymmetry in arch vortex behind 3D double-backward facing step [27].

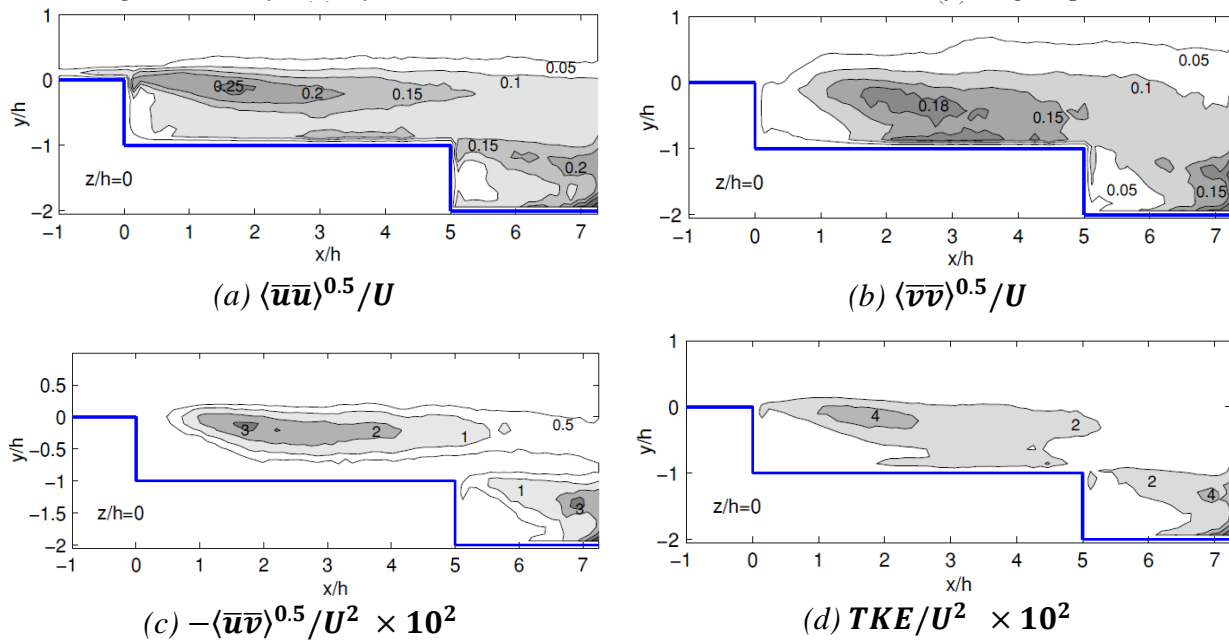


Figure 14: Contours of turbulence parameters for a 3D double-backward facing step [30].

## Wake Parametrization

Work has been previously performed at CDI to parametrize fluctuating velocity components in the airwake of a landing helicopter assault (LHA) class ship to allow for predictions of flow unsteadiness to circumvent computational and data storage limitations associated with CFD based solutions [31, 32]. The approach used a stochastic representation of the unsteady velocity components and a data reconstruction algorithm that preserved the spatial correlations relationships that resulted due to vortex structures in the ship airwake. Realistic velocity fluctuation predictions were obtained from the resulting model when compared to those obtained via CFD. The model however, was dependent on previously obtained CFD data and thus dependent on the configuration under consideration.

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A configuration independent methodology was proposed in an early publication by Woodfield et al. [33], where flow over the edges and faces of a ship structure were first characterized as one of three fundamental flow patterns depending on the incoming wind direction: corner flow (further categorized as separated or vortex corner flow), lee rotor flow and pressure drag flow, illustrated in Figure 15. Changes in mean velocities were then computed using a simplified standard deviation-based “turbulence” model for specified flow patterns, wind-over-deck angles, and ship dimensions. While only a curiosity comparison to wind tunnel data was presented, and indeed the need for further testing was emphasized, the authors noted that favorable responses were obtained from pilots during helicopter-shipboard simulations with this generic model.

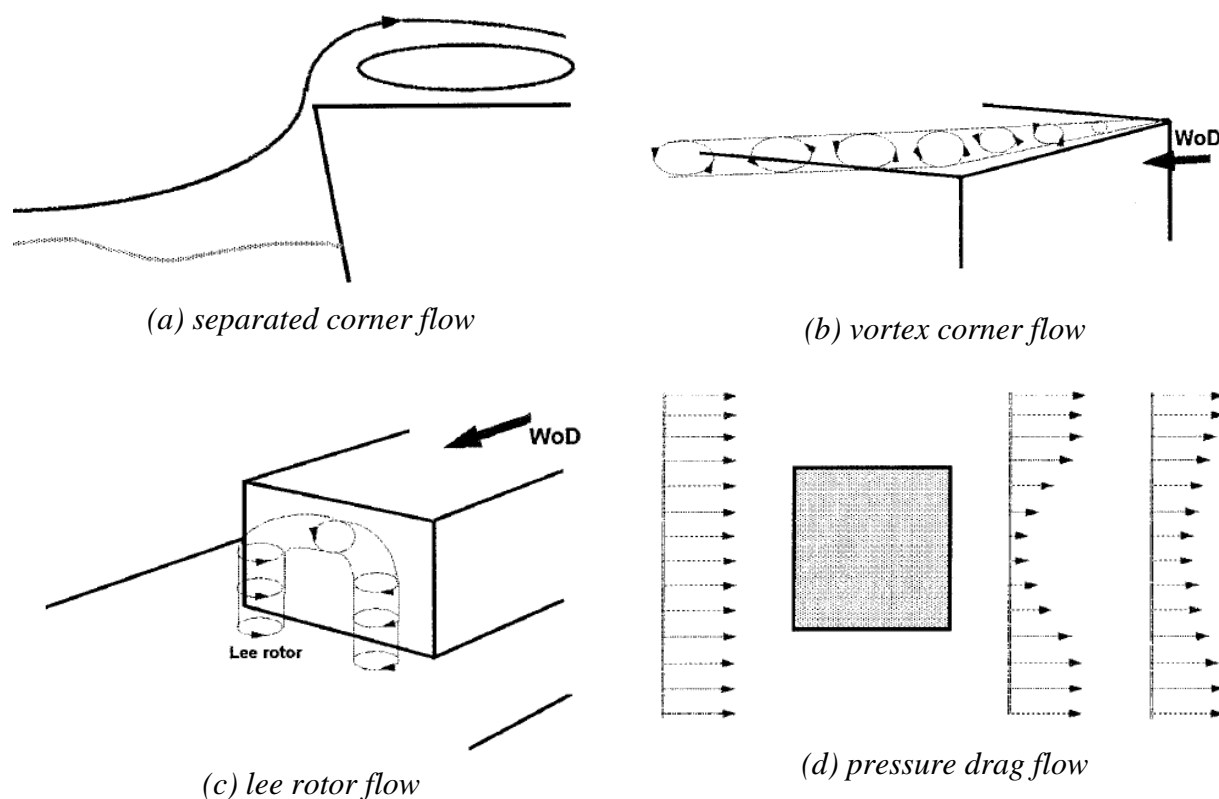


Figure 15: Flow patterns used to parametrize airwake in Ref. [33].

Generic airwake models have also been derived for flow in urban settings (e.g. Ref. [34]) and further review of relevant literature is needed at this point to identify parametrization techniques suitable for the project.

### **Plans for the Next Reporting Period**

In the next reporting period, we will continue to quantify the relevant flow structures, and will commence developing representative surrogate flow fields.

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## Appendix A: Kickoff Briefing



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

Kickoff Briefing

Glen Whitehouse

Continuum Dynamics, Inc.

Distribution statement A

Approved for public release: distribution unlimited

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March 29<sup>th</sup> 2021



## Overview

- 
- Motivation
  - Overall Goal
  - Background
    - Flight Dynamics for disturbance interactions
    - Disturbance modeling
  - Overview of the effort
    - Questions to be answered
    - Technical objectives and approach
  - Tasks
  - Summary

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## Motivation

- 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)
- Flight simulation has long been recognized as a valuable tool for augmenting engineering development and pilot training in DI operations
  - Most effective when the simulation model appropriately characterizes the 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”
  - Understanding and predicting the underlying physics
  - Trainer fidelity (i.e. can the pilot feel/tell a difference)



Daytime and nighttime dynamic interface operations

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## Overall Goal

- Goal is to quantify what is “good enough”
  - Fundamental aero-physics of a rotorcraft interacting with an external disturbance field
  - Quantify which length and time scales directly impact the aircraft’s fundamental response
  - Quantify what modeling fidelity is required to simulate interactions adequately
- Build upon ongoing/prior efforts that seek to quantify “good enough”
  - UMD/GIT focused on understanding the response of a wing to the wake shed by canonical structures
  - NAVAIR - Generalized Airwake Goodness Evaluation - sought to represent the entire DI scenario
  - Whitehouse and Brown looked at wake and disturbance modeling effects for a canonical isolated rotor
  - Wachspress, McKillip et al looked at developing a flight dynamics model for nearfield operations
  - Silva, Wachspress et al looked at flight dynamics for tiltrotor formation flight interactions
- Outcomes would enable the community to establish
  - The level of modeling fidelity required to adequately simulate disturbance interactions
  - CFD output requirements for ship airwake databases
  - Guidance that can be used to assist in specification of flying qualities, and aircraft performance requirements, such as ADS-33, DIPES and CETI

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## Background: Flight Dynamics Modeling

- Estimating the response of rotorcraft to gusts, atmospheric turbulence and disturbance fields has roughly followed "best practices" from fixed-wing community
  - Frozen field superposition
  - Assumes that time scales of the interaction are too short for mutual fluid dynamic interaction to occur
- Initial investigation focused on
  - Dynamic stability of the rotor
  - 1<sup>st</sup> order estimates of heave response to quantify ride quality
  - Estimates of stability derivatives for flight dynamics applications
    - Challenging to decompose aerodynamic derivative "gains" associated with only the gusts
- Modern approach
  - Component build-up model of the aircraft
  - Representation of aerodynamic components of the aircraft
    - Momentum theory and look-up table based models still most prevalent
    - Some demonstration cases using CFD (but rarely used due to time/computing constraints)
    - Effective state of the art is lifting surface model with a lagrangian wake and a panel method representation of the airframe

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## Background: Disturbance Modeling

- Frequency domain statistical representation (following frozen disturbance fixed-wing paradigm)
  - von Karman spectra
  - Dryden "white noise"
  - Jones' Statistical Discrete Gust method
- With the adoption of blade-element based aerodynamics models
  - 3D lookup table
  - 4D lookup table
  - But usually superposition and frozen field
- Distorting field (research)
  - Limited CFD investigations at NAVAIR and by Whitehouse and Brown (see next slide)
  - Particle method wake interacting with a lagrangian rotor wake
  - Usually limited to "proof-of-concept" or specific/limited applications



CASTLE / ExHel / CHARM visualization of shipboard operations

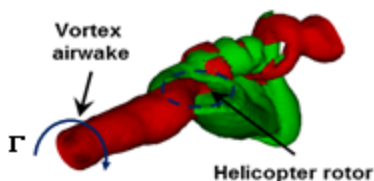
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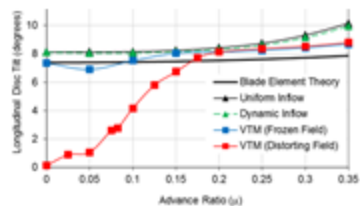
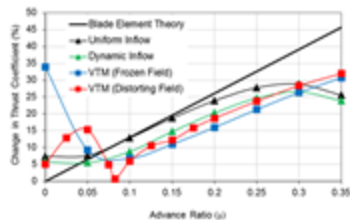
## Background: Disturbance Modeling (cont'd)

- Distortion of the wake and the disturbance can result in significant changes in aeromechanics
  - Function of "interaction time"
  - Function of relative strength
- Whitehouse and Brown investigated wake and disturbance modeling assumptions
  - Intention here is to build upon Whitehouse and Brown and work elsewhere to understand how these observations apply to more general cases



Wake distortion for a "parallel" wake vortex interaction

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Predicted change in thrust and longitudinal flapping as a function of forward speed for a "parallel"  $\gamma$  interaction



## Overview of the Effort: Questions to be answered

1. What spatial and temporal scales, present in a disturbance field, matter from Flight Dynamics and Flying Qualities standpoints?
  - Beyond the obvious constraints (i.e. larger than a rotor radius and those that induce velocities larger than the wake induced velocity)
2. How do these scales vary when the full aircraft is accounted for?
  - Helicopter response dominated by that of the rotor
  - May still be significant response associated with the fuselage, empennage and tail rotor
3. How do these scales vary with aircraft configuration/type?
  - Rotor response is  $\sim 90^\circ$  out of phase
  - Wing response is in phase
  - Integrated response also a function of nacelle angle for tiltrotor
4. How do these scales vary with aircraft flight condition, and can modeling simplifications be made without fundamentally changing the response?
  - e.g. is frozen field assumption acceptable above a certain speed?

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## Overview of the effort: Technical Objectives

1. Define spatial and temporal fluid dynamic scales and develop numerical representations (Year 1)
2. 6-DOF generic flight dynamics model assembly and testing (Year 1)
3. Define aeromechanics performance and FQ metrics, and simulation test matrix (Year 1-2)
4. Undertake simulation of a generic rotorcraft interacting with disturbance fields (Year 2)
  - Fundamental response
  - Helicopter
  - Tiltrotor
5. Develop realistic aircraft models and undertake simulations (Year 3)
  - Flight dynamics and flying qualities response
  - Helicopter
  - Tiltrotor
6. Documentation and dissemination of observations and conclusions (Years 1-3)

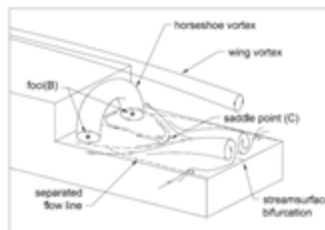
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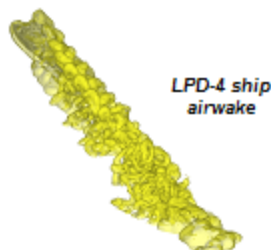


## Tasks

- **Task 1: Extended Technology and Requirements Review (Year 1)**
  - Solicit feedback regarding ONR's short- and long-term programmatic goals
  - Refine technical focus
- **Task 2: Definition of Disturbance Field Scales Relevant to Naval Rotorcraft Operations (Year 1)**
  - Usually think of problem in a quasi-steady manner
  - Unsteady and frequency content is also important
    - Pilot workload usually associated with responses in the 0.2-2Hz (1-10rad/s) range
  - Length scales are proportional to width of shedding structure
  - Frequency scales based on  $St \approx 0.2$
- **Task 3: Generation of Synthetic Disturbance Fields (Year 1)**



*Schematic of primary flow structures near to a small-deck ship*

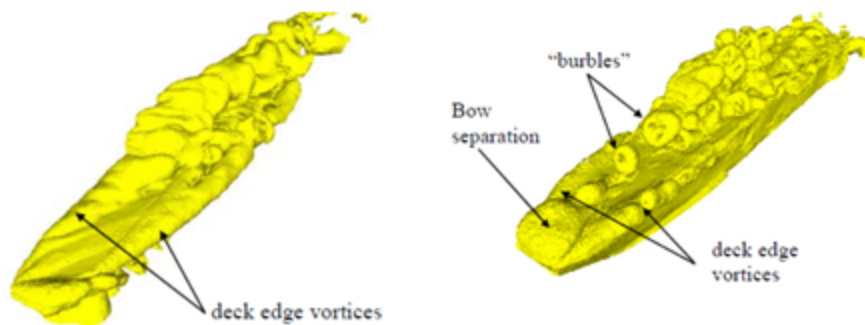


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# Tasks (cont'd)



Characteristic flow structures for a flat-top ship at two different WOD angles

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# Tasks (cont'd)

• Task 4: Definition of Aeromechanics and HQ Metrics (Year 1-2)

- Prior work looked at
  - ADS-33 for rotorcraft
  - S-Wake hazard rating for fixed wing
- Other (DIPES, CETI) ?

LEVEL	FLIGHT CONDITION		
	HOVER AND LOW SPEED	FORWARD FLIGHT	
		NEAR-EARTH	UP-AND-AWAY
1	3° roll, pitch, yaw 0.05g to 0.1g No recovery action for 3.0 sec	Both Hover and Low Speed and Forward Flight Up-and-Away requirements apply	Stay within OFF. No recovery action for 10 sec
2	10° attitude change or 0.2g acceleration. No recovery action for 3.0 sec	Both Hover and Low Speed and Forward Flight Up-and-Away requirements apply	Stay within OFF. No recovery action for 5.0 sec
3	24° attitude change or 0.4g acceleration. No recovery action for 3.0 sec	Both Hover and Low Speed and Forward Flight Up-and-Away requirements apply	Stay within OFF. No recovery action for 3.0 sec

ADS-33E Handling Qualities Requirements for the Transient Motion Following the Failure of a Flight Control System Component

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Wake Vortex Hazard Assessment Rating Scale		Page 1
Hazard Assessment Rating Scale		
Levels	Description	Rating
Approach limits not exceeded	No disturbance experienced, no pilot reaction required	①
Approach limits exceeded	Slight disturbance, moderate pilot reaction required	②
	Moderate disturbance, considerable pilot reaction required	③
Go Around performed	Go around maneuver performed without exceptional pilot skills	④
	Go around maneuver performed with considerable corrective actions for aircraft recovery (critical flight state (altitude, rate, coordination))	⑤
	Temporarily or total loss of control (crash if close to ground)	⑥
Approach Limits		
Bank angle:	$\theta \leq 10^\circ$	
Vertical speed:	$ \dot{h}  \leq 300 \text{ ft/min}$	
Pitch Attitude:	$-2.5^\circ \leq \alpha \leq 10^\circ$ (pitch dependent), example 4 for A320	
Approach speed:	$V_{app} \leq 1.05 V + V_{min} + 1200$	
Lateral deviation:	$\Delta L_{lat} \leq \pm 0.75 \text{ km}$	
Down slope deviation:	$\Delta \text{DSD} \leq \pm 150 \text{ ft}$	
Angle of climb:		

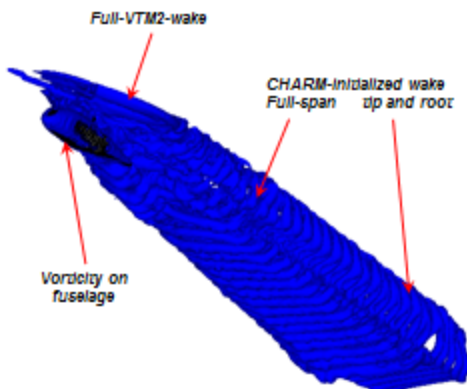
Fixed-Wing Wake Vortex Hazard Assessment Rating Scale (Luckner et al 2003)



## Tasks (cont'd)

- **Task 5: Generic FD Model Assembly (Year 1-2)**

- Currently envisioned to be CASTLE coupled to CHARM and VTM2
  - Might get replaced with alternative generic FD model under development elsewhere
- Aircraft types
  - Helicopter
  - Tiltrotor
- Tiers of analysis fidelity
  - Finite state wake & frozen disturbance field
  - Free wake model & frozen disturbance field
  - CFD wake model & frozen disturbance field
  - Free wake model coupled & distorting (particle method) disturbance field
  - CFD wake model coupled & distorting (CFD) disturbance field



Schematic of VTM2 and sample prediction for ROBIN-like configuration

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## Tasks (cont'd)

- **Task 6: Fundamental Helicopter Response (Year 2)**

- Fixed controls, with constrained motion for "worst case"
- Configuration permutations
  - Isolated main rotor
  - Main rotor and tail rotor
  - Rotors and fuselage (lookup table)
  - Rotors and fuselage (panel method for the fuselage)

- **Task 7: Fundamental Tiltrotor Response (Year 2)**


- Fixed controls, with constrained motion for "worst case"
- Repeat task 6 permutations, but also include the wing

- **Task 8: Helicopter Flight Dynamics Response (Year 3)**

- Aircraft specific properties (e.g. weight, control system etc.) where aircraft can move
- Repeat task 6

- **Task 9: Tiltrotor Flight Dynamics Response (Year 3)**

- Aircraft specific properties (e.g. weight, control system etc.) where aircraft can move
- Repeat task 7

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## Schedule

Task	CY21		CY22				CY23				CY24	
	FY21		FY22		FY23		FY23		FY24			
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
1. Extended Technology and Requirements Review												
2. Definition of Disturbance Field Fluid Dynamics Scales Relevant to Naval Rotorcraft Operations												
3. Generation of Synthetic Disturbance Fields												
4. Definition of Aeromechanics and HQ Metrics												
5. Generic FD Model Assembly												
6. Fundamental Helicopter Response												
7. Fundamental Tiltrotor Response												
8. Helicopter Flight Dynamics Response												
9. Tiltrotor Response												
<b>Management and Documentation</b>												
Kickoff briefing with ONR on board	X											
Annual Progress reports to ONR				X			X					
Final report												X
Annual Visits and briefings at ONR		X			X				X			
Final briefing at ONR												X
Presentation of results at technical conferences (Mar)					X				X			



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## Summary

- Flight simulation is a valuable tool for engineering development and pilot training
  - Most effective when the simulation model appropriately characterizes the interactions
- How do we know if model “appropriately characterizes the interactions”?
  - Underlying physics
    - Do we understand the phenomena and can we predict the physics?
  - Trainer fidelity
    - Can we implement sufficient fidelity and can the pilot feel/tell a difference?
- Goal of this effort is to quantify what is “good enough”
  - Fundamental aero-physics of a rotorcraft interacting with an external disturbance field
  - Quantify which length and time scales directly impact the aircraft’s fundamental response
  - Quantify what modeling fidelity is required to simulate interactions adequately
- Outcomes would enable the community to establish
  - The level of modeling fidelity required to accurately simulate disturbance interactions
  - Guidance that can be used to assist in defining requirements for trainers, training, flying qualities and handling qualities



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