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14. ABSTRACT Highly mixed turbulent bubbly flows in the near and far field of a ship have become a critical consideration in the design of the modern Naval surface ship. While the prediction (and detection) of the bubbly cloud is most relevant for the far-field wake, it is the near-field ship geometry and motions that provide the source of this bubble field. While there have been major advances in both the prediction of the near-field ship flow and the evolution of the far-field bubbly wake, physics-based modeling and efficacious design closure bridging these two regions remain a significant challenge. This strategically focused effort aims to bridge this gap in Computational Ship Hydrodynamics (CSH) capability.					
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Contract Information

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Principal Investigator	Dick K. P. Yue
Organization	Massachusetts Institute of Technology

Technical Section

Technical Objectives

Highly mixed turbulent bubbly flows in the near and far field of a ship have become a critical consideration in the design of the modern Naval surface ship. While the prediction (and detection) of the bubbly cloud is most relevant for the far-field wake, it is the near-field ship geometry and motions that provide the source of this bubble field. While there have been major advances in both the prediction of the near-field ship flow and the evolution of the far-field bubbly wake, physics-based modeling and efficacious design closure bridging these two regions remain a significant challenge. This strategically focused effort aims to bridge this gap in Computational Ship Hydrodynamics (CSH) capability.

Specifically, our technical objectives are the following:

- I. Development of validated (pseudo-)DNS and implicit-LES tools for the prediction of the near-field highly-mixed multi-phase turbulent flows.
- II. Obtain extensive CSH datasets that characterize the near-field bubble entrainment and multiphase flow evolution (including steady and unsteady bow breaking waves, and separated stern flows). Develop analysis tools to obtain bubble field quantifications and statistics from the datasets.
- III. Develop (two-phase flow) variable-density turbulence (VDT) closure and computational models to enable intermediate-field predictions utilizing new LES and RANS with these models embedded.
- IV. Obtain parameterization of the air entrainment and bubble source for use in large-scale applications that account for the effects of ship geometry and speed/motion parameters on the downstream bubble field.

This development will provide the essential physical understanding, models and tools that bridge the gap between the near-ship multiphase turbulent flow and the far-field bubbly flow quantification necessary for the long-time large-scale evolution and prediction of the bubbly wake.

Technical Approach

This effort is made possible by recent advancements in computer hardware and numerical methods that enable high-resolution simulations of the ‘macro-scale’ near-field flow including the early time-history of the air entrainment. Such simulations can be viewed as DNS, or more precisely implicit-LES (iLES), of the bubble-laden turbulent flow characterized by the physical scales greater than the Hinze scale $a > O(a_H)$. The computational method employed is a Cartesian grid method based on interface capturing techniques such as the Asymmetric Level Set method and conservative Volume of Fluid Method and an immersed boundary method called the Boundary Data Immersion Method. This method has been used on high-resolution grids to obtain detailed flow information for highly variable density turbulent flows.

Additionally, to complement these advanced numerical solvers, a suite of analysis tools have been developed and *a priori/a posteriori* testing of closure models have been performed. To study the Lagrangian statistics of entrained air in Cartesian grid simulations, a data mining technique based on computer image blob extraction algorithms has been developed. To obtain parametric correlations from large high-fidelity data sets to enable effective semi-empirical predictions, we have recently developed methods for establishing such parametric models based on combining machine learning techniques with physics-based models of fluid flows.

To achieve the stated objectives, a number of key scientific and technical issues and tasks were outlined in the proposal that must be addressed and accomplished:

1. Development of iLES tools for the prediction of the near field highly mixed multi-phase turbulent flows. This will require the following tasks:
 - i. Extend the existing Cartesian-grid immersed boundary and interface capturing techniques to enable simulations of $a \sim O(a_H)$ bubble sizes in the context ship-scale simulations. The purpose being to achieve sufficient resolution in the context of the variable density flows without the need for modeling assumptions or closure.
 - ii. Performing validation of these new capabilities by comparisons to benchmark canonical air entrainment flows such as a vertical surface impinging jet for which detailed experiment data are available.
 - iii. Obtain bubbly wake solutions at multiple grid levels to understand the limitations of numerical Hinze scaling and the requirements for resolution and convergence.
2. Development of an extensive database of high-resolution ship bubbly and highly mixed turbulent flows. This database, generated by iLES, will incorporate a broad range of canonical problems which includes:
 - i. Unsteady breaking waves involving the formation of an initial air cavity and its subsequent break down. This provides a canonical example of large-scale air entrainment.
 - ii. Quasi-steady breaking bow waves where air entrainment occurs as a result of air cavity formation, as well as impacting jets, droplets and sprays.
 - iii. Wetted and dry transom stern flows where inertia and shear layers and violent free-surface turbulence are important for air entrainment.
3. Analysis of the dynamics of highly mixed turbulent flows. The primary focus of this effort will be to elucidate the dynamics of the entrained air in the presence of high void fractions and significant turbulent fluctuations. Bubbly flow metrics of particular interest include:
 - i. The frequency and quantity of air entrainment for quasi-steady breaking such as that seen in breaking bow waves and stern flows and its dependence on geometric parameters.
 - ii. The time and ensemble fluid phase statistics (air/water intermittency) in highly mixed HVT flows and its relation to air entrainment.
 - iii. Effect of turbulence fluctuations on the breakup of bubbles.
4. Development of VDT RANS closure and LES SGS models to extend the predictive range down through the inertial zone. The appropriate closure models for VDT (LES and/or RANS) will be tested in both *a priori* and *a posteriori* fashion. Key effects and efforts that must be considered include:
 - i. Developing LES SGS models for mass, momentum and interface capturing to account for the effects of mass flux and VDT.
 - ii. The effect of mass and momentum transferred from the LES simulation to the SGS model as bubbles become under-resolved, passing through the numerical Hinze scale.

- iii. URANS closure modeling by analysis of the variable density Reynolds Stress Transport (RST) equations by considering both the implicit and explicit algebraic Reynolds stress models, in terms of the anisotropic stress tensor to reveal the relevant modeling assumptions and guide the selection of appropriate closure models.
 - iv. *A priori* testing of the variable density turbulent kinetic energy equation, a subset of the RST equations, as well as of the LES SGS mass and dissipation equations.
 - v. *A posteriori* testing of VDT closures for model problems in the iLES database.
5. The development of semi-empirical air entrainment and bubble source models useful for large-scale simulation of bubbly flows where resolved simulations of even the largest scale bubbles are expensive. Separate elements of this include:
- i. Develop and run a complete test matrix of geometry, speed, and motion parameters for select physical problems for parameterization of the iLES/LES database.
 - ii. Develop new physics-based air-entrainment models to capture the dominant scaling laws and transport processes across a number of flow regimes.
 - iii. Utilize the PBLM approach to parametric modeling to mesh the new quantitative data and physics based models into robust and accurate semi-empirical bubble cloud evolutionary models.

Progress Statement Summary

We developed iLES tools for the prediction and analysis of the near-field, mixed multiphase turbulent flow region in the wake of a transom stern. These tools were utilized to develop an extensive database of high-fidelity ship bubbly and highly mixed turbulent flows of the dry transom stern flows. The analysis of the database enabled us to determine the flow structure in the highly mixed region of the rooster tail has been determined. Progress has been made in establishing the scaling of the air entrainment and wake characteristics in the near field of a dry transom stern geometry. Closure models for the incompressible VDT (variable density turbulence) for URANS models have been developed and tested *a priori* for turbulent mass flux and kinetic energy.

The iLES simulations of transom sterns elucidated the spatial, temporal and turbulent characteristics of the mixed flow region in the near wake of a surface ship as well as established the importance of turbulent mass flux and anisotropy in the wake that has guided the development of URANS closure models. This represents a significant/foundational step forward in addressing the scientific and technical issues related to multiphase turbulence modeling for Computational Ship Hydrodynamics.

Progress

As a reference for the problem considered, figure 1 shows isosurfaces of the half volume fraction $f=0.5$ that represents the interface for two different iLES simulations of a canonical transom stern with half-beam to draft ratio $B/D=1$. Both cases are considered to be dry transom conditions. The figure elucidates the wake dependence on speeds: (i) rooster tail location is further downstream in the wake at high speeds; (ii) the wake width is wider for lower speeds; (iii) the presence of convergent corner waves off of the stern corners at both speeds; and (iv) the presence of the divergent wave train within the computational domain for the slower speed.

The average wake flow features inside the mixed phase region of the rooster tail (Figure 2) shows the flow structure to be partially consistent to the flow structure of breaking waves, which is typically described as a roller-bore structure sitting on top of a dividing streamline. And partially consistent with that of a hydraulic jump, which is a plane mixing region of fast moving lower liquid in a quiescent upper liquid. Figure 2 shows a weak roller-bore at the head of the rooster tail with a strong coherent vortex structure in the far wake of the rooster tail. The rooster tail itself however shows a wake deficit or jet

structure inside the mixing region, which has never been reported. Temporal analysis of the vorticity in the far wake plane mixing area shows the convective velocity is consistent with that of a high speed flow mixing into a quiescent fluid and the fundamental frequency of the wake is at a Strouhal number of 0.2.

To differentiate between mixing due to temporal fluctuation of the interface or actual entrained air cavities or spray droplets in our analysis, we developed a novel Lagrangian technique for identifying contiguously connected cells. Figure 3 shows a representative result using this technique. A temporally averaged surface that is fluctuating but not entraining air obtains an average mixed region. Figure 3 highlights the difference between mixing due to a temporal fluctuation of the interface (figure 3a) or due to entrained air/spray droplets (figure 3b). The Lagrangian cavity identification method enables us to calculate the volume of entrained air and one-dimensional surface entrainment rate. Figure 4 shows the total volume entrained and asurface entrainment rate, which is estimated based on the one-dimensional flux of the volume of entrained air. When scaled by the draft Froude number, the initial peak entrainment rate collapses to a single point (the point where the convergent corner waves collide at the centerline) and similar value for all of the speeds and geometries in our study.

Developing turbulent closure models of IHVDT hinges on the understanding the characteristics of the turbulent mass flux (TMF). The analysis of the turbulent mass flux (TMF) and IHVDT in the wake of a stern using the method of invariants and our redefined turbulent anisotropy tensor shows that the flow is highly anisotropic near the breaking of the convergent corner waves rooster tail region and then the flow becomes more isotropic as the wake evolves downstream. This varying nature of anisotropy/isotropic features is consistent for the speed and geometries considered to date and collapses with Froude and geometric scaling. LES and RANS closure models must capture the changing characteristics of the IHVDT along the wake. *A priori* data analysis of classical gradient diffusion closure models confirmed expectations that correlation between the TMF and gradient diffusion models is weak, especially in more anisotropic regions.

Our modeling effort focuses on determining an algebraic model for TMF based on incorporating anisotropic effects into the deformation tensor D_{ij} using the anisotropy tensor b_{ij} . Figures 5 and 6 show that our newly developed anisotropic model captures salient features in the TMF not captured by the isotropic model. The anisotropic model also outperforms the isotropic model even in the more isotropic far wake region. Development of this type of IHVDT closure model has implications outside of IHVDT in the sense that TMF exhibits counter gradient behavior seen in premixed combustion and the turbulent boundary layer formed in slot injection systems. Historically, modeling counter gradient behavior has been empirical in nature. The IHVDT closure model developed as a part of this work may also provide a physics-based model for these applications.

Figures

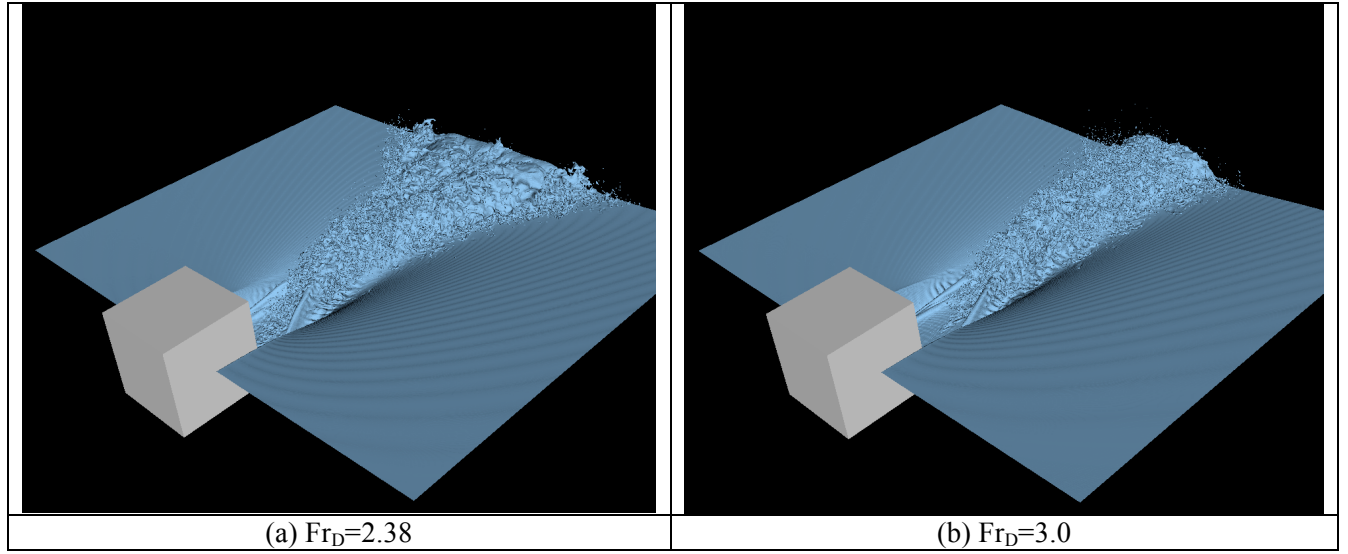


Figure 1. Instantaneous interface behind canonical transom stern with $B/D=1$ at two different speeds from iLES simulation.

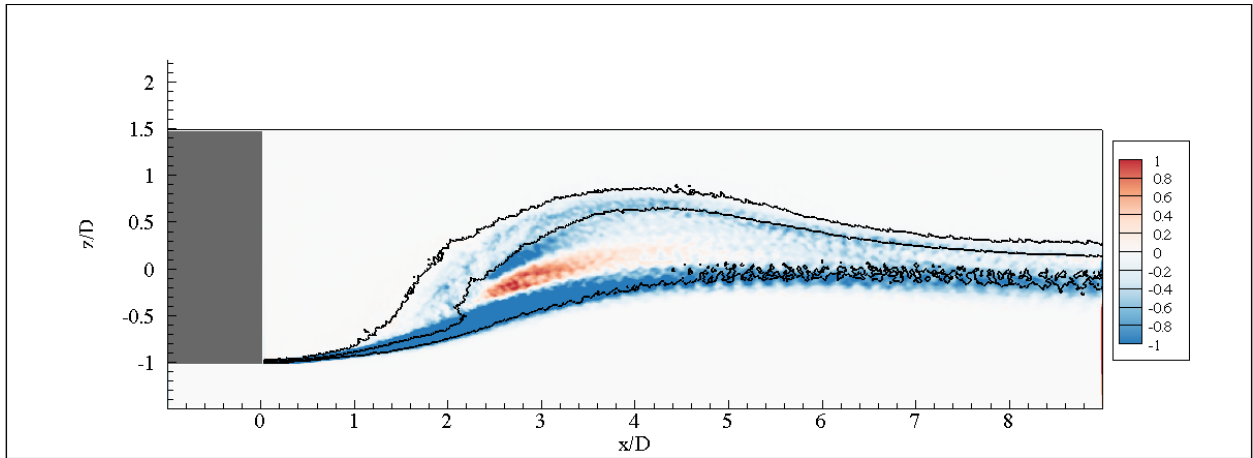
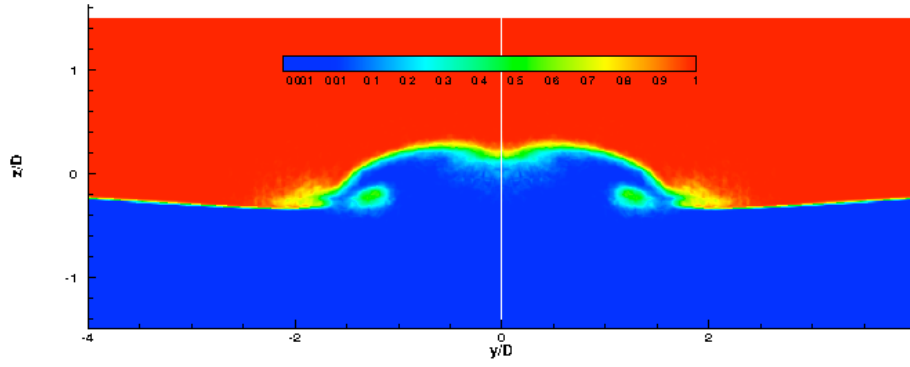
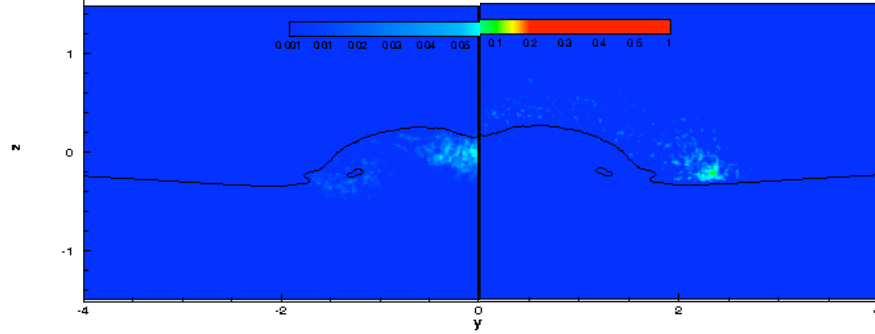


Figure 2. Average density weighted transverse vorticity on the centerline of the wake for a transom stern at $Fr_D=2.53$ simulated with iLES, BDIM and cVOF. Black lines represent the bounds of the average mixing region (from top to bottom) at $f=(0.05, 0.5, 0.95)$.



(a) Temporal average of volume fraction f



(b) right: average void fraction due to entrained air
left: average spray fraction due to spray droplets

Figure 3. Representative result using developed Lagrangian air cavity/spray droplet identification algorithm. The temporal fluctuation of the interface provides a significantly different average void fraction (a) than that determined using the identification algorithm (b). View is looking upstream from at $X/D=7.2$. Black line in (b) represents the average interface location.

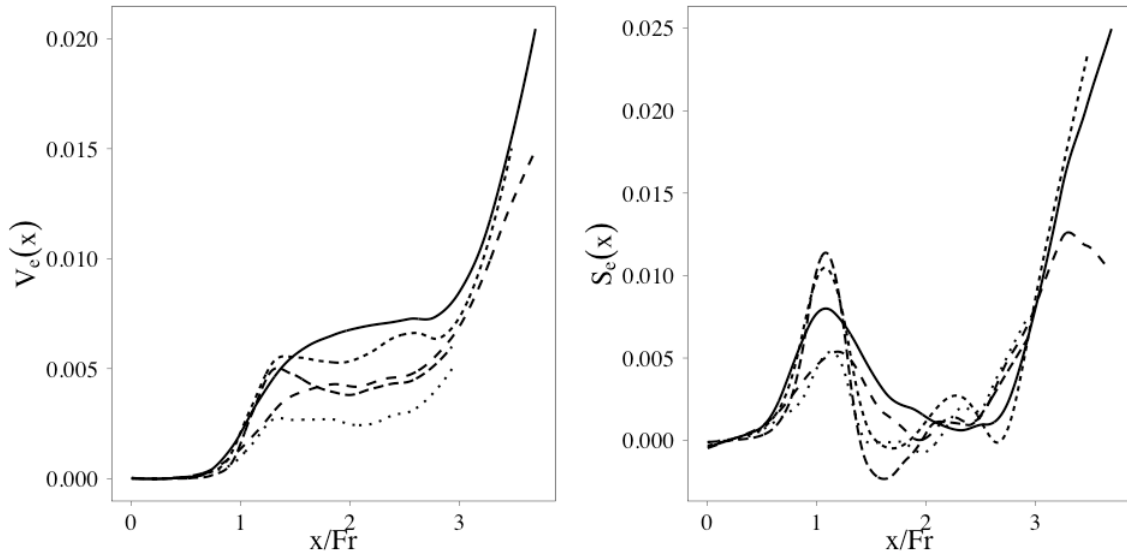


Figure 4. Scaled total entrained volume and surface entrainment rate for the speed dependent cases in the study.

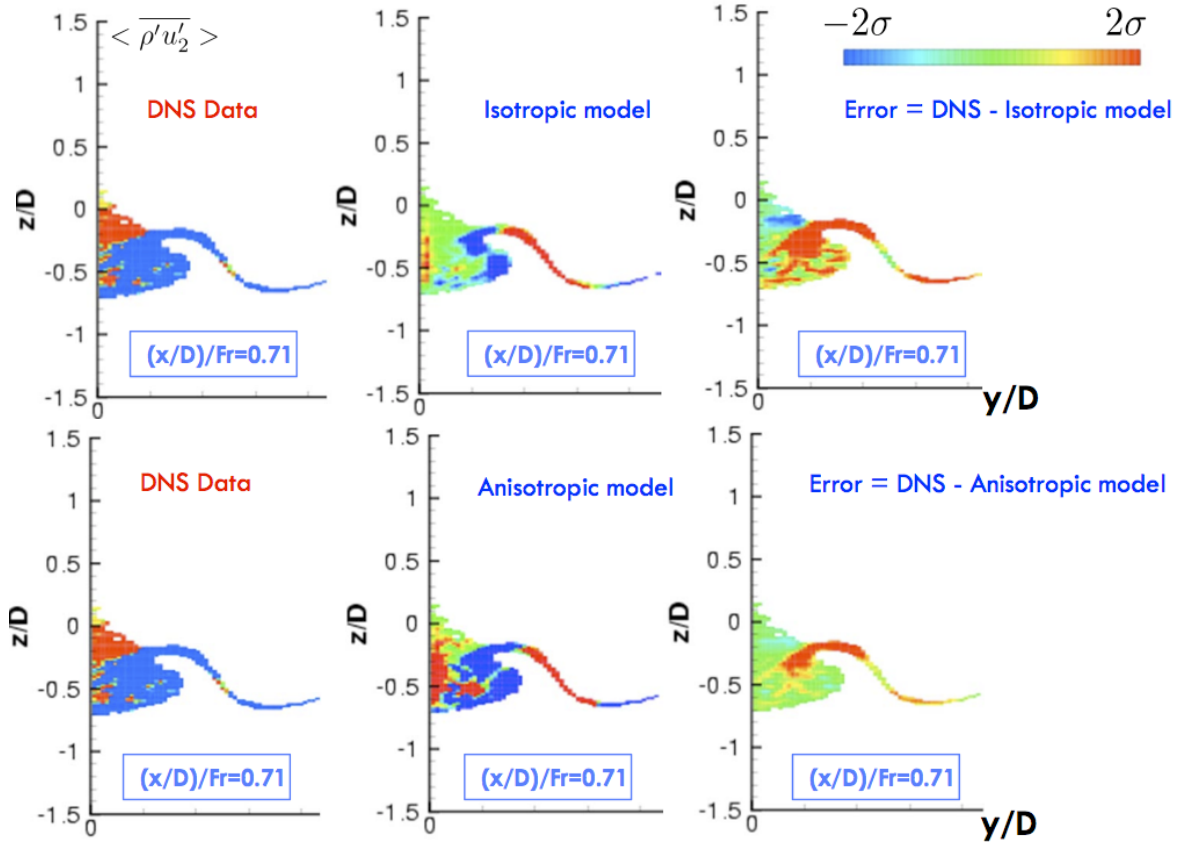


Figure 5. Performance of the isotropic and newly developed anisotropic model compared to iLES datasets at a location prior of peak anisotropy.

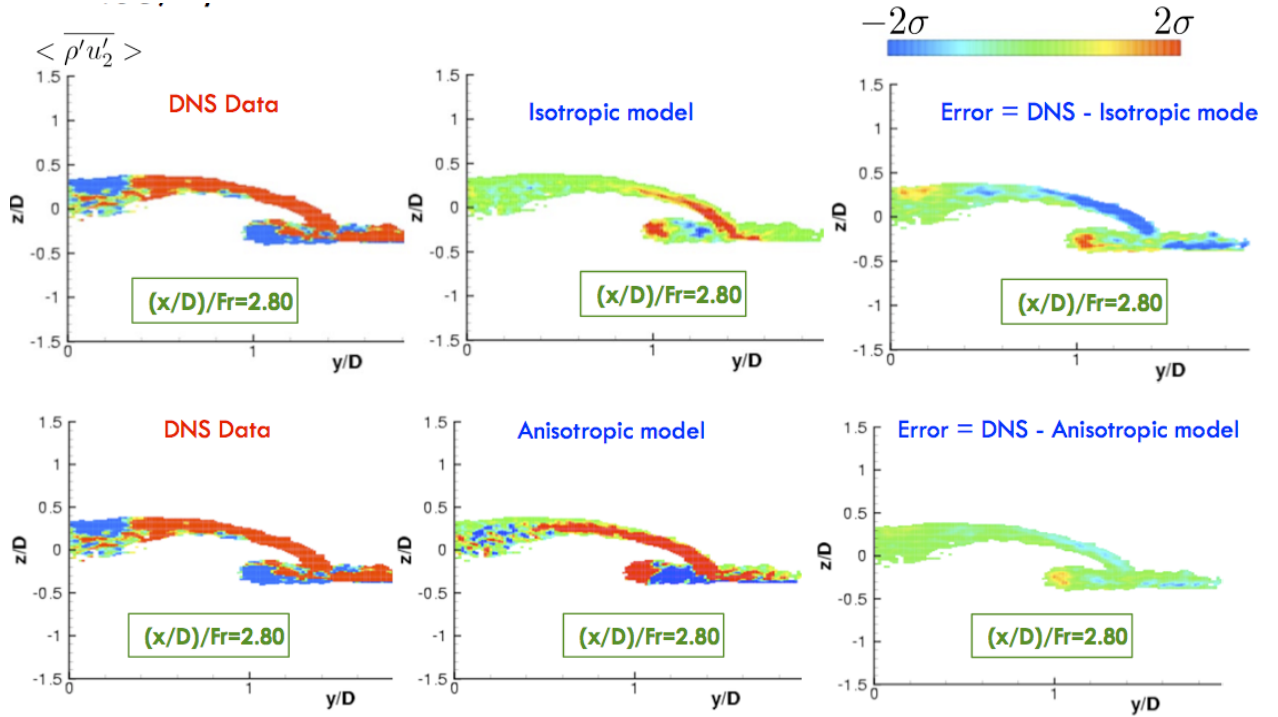


Figure 6. As in Figure 5 at a location further downstream in the wake.

Publications

1. Hendrickson, K., Weymouth, G., Yue, D. K.P. (2013) Analysis of the two-phase flow in the wake of a transom stern. 66th Annual Meeting of the American Physical Society Division of Fluid Dynamics, Pittsburgh, PA.
2. Hendrickson, K. Weymouth, G., Banerjee, S., and Yue, D.K.-P. Air Entrainment and Multiphase Turbulence in the Bubbly Wake of a Transom Stern. *International Shipbuilding Progress*. 60(1), 375-401.
3. Hendrickson, K. Weymouth, G., Banerjee, S., and Yue, D.K.-P. (2012). Air Entrainment and Multiphase Turbulence in the Bubbly Wake of a Transom Stern. To appear in, Proc. 29th Symposium on Naval Hydrodynamics, Gothenburg, Sweden, Selected for special issue of *International Shipbuilding Progress*.
4. Weymouth, G., Hendrickson, K., Banerjee, S., and Yue, D.K.-P. (2010). Bubble Source Modeling Using Macro-Scale Two-Phase Flow Simulations. *Proceedings of the 28th Symposium on Naval Hydrodynamics*, Pasadena, CA.
5. Hendrickson, K., Weymouth, G., and Yue, D. K.P. Flow Structure and Air Entrainment in Large-Scale Three-Dimensional Dry Transom Stern Wakes. *To be submitted*.
6. Hendrickson, K., Banerjee, S. and Yue, D. K.P. Modeling of Incompressible Highly Variable Density Turbulence in the wake of a Dry Transom Stern. *To be submitted*.
7. Hendrickson, K. and Yue, D. K.P. Scaling of the Wake Characteristics and Air Entrainment of Three-Dimensional Dry Transom Stern Wakes. *In preparation*.

Students Graduated

Two Ph.Ds

