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**Final Report: ONR N00014-19-1-2151****High Reynolds Number Stratified Wake Studies****PoP: 25-MAR-2019 – 30-MAR-2020**

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[alan.brandt@jhuapl.edu](mailto:alan.brandt@jhuapl.edu)**OBJECTIVE AND OCEANOGRAPHIC RELEVANCE****Long Term Goals**

This grant is part of a long-term effort to advance understanding of internal wave source mechanisms and the evolution and propagation of internal waves under environmental conditions representative of the ocean. Results of this study will support the scientific basis for phenomenology relevant to applied Navy programs involving hydrodynamics and provide data for validation of theoretical/numerical models.

**Objective**

This effort was built upon prior grants, where properties of the early-time, high Reynolds number ( $Re$ ) stratified wakes were measured in order to: (1) investigate the properties of the high- $Re$  stratified turbulent wake of a towed sphere as a function of distance downstream, and (2) characterize the internal wavefield (IW) generated by the turbulent wake of a towed sphere under steady and non-steady (turning/accelerating) conditions.

**SUMMARY OF ACCOMPLISHMENTS**

Turbulent and mean flow field data in the near-field stratified wake of a sphere at  $Re$  up to  $1.2 \times 10^6$  were obtained – values far exceeding those of prior studies and coming closer to  $Re$  values of full-scale vehicles. Data previously obtained from multiple deployments at Triadelphia reservoir (at the facility operated by NSWC/Carderock) were analyzed in detail (Brandt & Kalumuck, 2016; Brandt, 2018), and a manuscript for publication is under development. A small subset of these data

was utilized in a collaboration for comparison with LES calculations of researchers at Leidos, Inc., the results of which will be presented at the upcoming Naval Hydrodynamics symposium (Conroy, et al. 2018). New data at a range of downstream distances was obtained from experiments at the Ohmsett salt water tow tank that is thermally stratified in summer. Analysis of these data is currently in progress. A short summary of accomplishments is provided here. Additional details were presented at the 2018 and 2019 ONR 331 Hydrodynamics Program Reviews (Brandt, 2018; Brandt & Kalumuck, 2019).

## Experiments at Triadelphia

### Detailed analysis of previously obtained data.

Data obtained in earlier deployments at Triadelphia reservoir were processed and analyzed in detail to obtain spectra of the fluctuating turbulent  $u$ ,  $v$ , and  $w$  velocities at  $x/D = 5.3$  along the wake centerline and at a location near the wake edge ( $0.45 D$  above the centerline). All three spectral components at both locations were found to exhibit an inertial range (denoted by its  $-5/3$  slope) over about an order of magnitude in wavenumber extending down to scales of a few cm. Temperature fluctuation spectra from a vertical array of 7 thermistors were also found to exhibit the  $-5/3$  inertial subrange.

Large values of the turbulent energy dissipation ( $\sim 5 \times 10^{-4} - 10^{-2} \text{ m}^2/\text{s}^3$ ) were found from the measured near field velocity spectra. Spectral amplitudes and dissipations were found to increase with  $Re$  (as expected) approximately three-fold for a factor of 2 increase in Reynolds number. The spectral amplitudes and dissipations were found to be consistently larger along the wake centerline than nearer the wake edge (approximately three times larger). Dissipation scaled by the sphere diameter and the cube of the mean tow velocity were found to vary as  $Re^{-1}$  at the centerline and as  $Re^{-1.5}$  near the edge.

## Experiments at Ohmsett

A new test rig was designed, fabricated and assembled for measurement of turbulent sphere wake velocities and temperature fluctuations at variable downstream distances in the Ohmsett thermally stratified salt water tow tank. The rig consisted of two adjustable frame assemblies that separately held the sphere and the wake instrumentation suite. The instrumentation suite included 4 Acoustic Doppler Velocimeters (ADV) each measuring the fluctuating  $u$ ,  $v$  and  $w$  velocities and 13 fast response thermistors arrayed on a vertical slice through the wake. Data were collected at 200 Hz. A CTD probe measured the thermal stratification profile. The distance between the sphere and measurement suite was varied by changing the distance between the linked main and auxiliary carriages.

A week of experiments were conducted in July 2017 produced a total of 39 runs spanning a parameter space that included downstream distances between 5 and 20 diameters, and Reynolds numbers ( $Re_D$ ) between  $2.3 \times 10^5$  and  $1.4 \times 10^6$ , as well as background measurements with the sphere removed. Stratification varied from unstratified to  $0.4 \text{ }^\circ\text{C/m}$  ( $0.04 \text{ rad/s}$  or  $26 \text{ cph}$ ). Issues regarding the signal-to-noise ratio of the turbulent velocity measurements have been uncovered and are being investigated. Further analysis of these data are in progress.

## **PUBLICATIONS AND PRESENTATIONS RESULTING FROM THIS STUDY**

Brandt, A. 2018 “Internal Gravity Wave Generation by Impulsive Forcing / High Reynolds Number Stratified Wakes,” 2018 ONR 331 Hydrodynamics Program Review, San Diego, 18-22 June 2018.

Brandt, A. and K.M. Kalumuck, “High Reynolds Number Stratified Wakes,” ONR 331 Hydrodynamics Program Review San Diego CA, 19 June 2019.

Brandt, A. and Kalumuck, K.M. 2016 “High Reynolds Number Stratified Wakes,” presentation and conference paper, VIII<sup>th</sup> International Symposium on Stratified Flows, San Diego, CA, Aug. 29 - Sept. 1, 2016.

Brandt, A., Kalumuck, K.M., “High Reynolds Number Stratified Wakes,” presentation at ONR Program Review, Arlington, VA, 8-10 March 2017.

Conroy, D.T., J.W. Rottman, L.K. Brandt, A. Brandt and K.M. Kalumuck, “High Reynolds Number Stratified Wakes: Comparisons of Numerical Simulations with Field Experiments,” 32<sup>nd</sup> Symposium on Naval Hydrodynamics, Hamburg, Germany, 5-10 August 2018.

Kalumuck, K.M. and A. Brandt, “High Reynolds Number Stratified Turbulent Sphere Wake Measurements,” Abstract submitted, 72<sup>nd</sup> Annual Meeting American Physical Society, Division of Fluid Dynamics, Seattle, WA 23-26 November 2019.

Kalumuck, K.M., A. Brandt, K.R. Shipley, K.S. Decker, “Measurement of High Reynolds Number Near-Field Turbulent Sphere Wakes under Stratified Conditions,” 68<sup>th</sup> Annual Mtg., Am. Phys. Soc. Div. Fluid Dynamics, Boston, MA, November 22-24, 2015.

Kalumuck, KM, Brandt, A, “Measurement of High Reynolds Number Stratified Wake of a Towed Sphere,” 70<sup>th</sup> Annual Mtg. Am. Physical Society Division of Fluid Dynamics, Denver, CO, 19-21 November 2017.